Energy Research and Development Division
FINAL PROJECT REPORT

ENERGY INNOVATIONS SMALL GRANT PROGRAM: 2006 INDEPENDENT ASSESSMENT REPORTS

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Prepared by: San Diego State Research Foundation

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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The Energy Research and Development Division conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The Energy Research and Development Division strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

Energy Research and Development Division funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Energy Innovations Small Grant Program: 2006 Independent Assessment Reports is the final report for the Energy Innovations Small Grant Program project (contract number 500-98-014) conducted by San Diego State University Research Foundation. The information from this project contributes to Energy Research and Development Division's RD&D Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

The California Energy Commission has been conducting the Public Interest Energy Research (PIER) program through competitive solicitations to advance science or technology in each of the seven PIER program areas to benefit California ratepayers since 1997. In addition, the Energy Commission has also funded and managed the Energy Innovations Small Grant (EISG) Program since 1998. The role of the EISG program is to advance research into new and innovative energy concepts and technologies whose feasibility is not yet sufficiently established to meet traditional research and development (R&D) funding requirements.

The Energy Innovations Small Grant (EISG) program supports early-phase development of promising new energy technology concept. This category of projects is not covered by PIER general solicitations that focus primarily on development of established concepts. Qualifying EISG projects address one of the defined PIER RD&D areas. If the feasibility of an innovative energy concept is proven through the EISG project work, then traditional R&D funding may become available to further develop the project.

Independent Assessment Reports (IARs) are written at the completion of every EISG grant project. These reports outline the objectives of the project, discuss the successes and failures, and offer recommendations for potential future work. This report presents a collection of 23 independent assessment reports for EISG grant projects awarded during 2006.

Keywords: Ratepayer, California Energy Commission, Energy Innovations Small Grant, EISG, Independent Assessment Report, IAR, Public Interest Energy Research, PIER RD&D, electricity, natural gas, transportation, research, energy technology concepts, project, market, outcomes, conclusions, benefits

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EXECUTIVE SUMMARY

The Energy Innovations Small Grant (EISG) program is a component of the Public Interest Energy Research (PIER) Program managed by the California Energy Commission. The PIER Program benefits California electric and gas ratepayers by funding energy research, development, and demonstration (RD&D) projects that are not adequately provided for by the competitive and regulated energy markets.

The Energy Commission recognizes the need for a program to support the early development of promising new energy technology concepts that are not mature enough to be covered by PIER general solicitations. The Energy Commission has established the EISG program to meet this need.

This report is a compilation of the Individual Assessment Reports (IARs) for grant projects that were awarded in 2006 and that have not been previously published.

All data sources for tables and figures are from the author unless otherwise noted.

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CHAPTER 1:
Introduction

2006 EISG Projects with IARs Included in this Section

Project	Researcher	EISG Funding
Electric Service Reliability Analysis Tool	Angela Chuang	$50,000
Development of High-Performance Magnesium Diboride-Based Superconductor/Metal Matrix Composite Components for use in Superconducting Fault Current Limiters	Nove Technologies, Inc	$95,000
Development of an Ordered Thin Film Palladium Alloy Membrane for Hydrogen Separation	ITN Energy Systems	$94,949
Ultra Low NOx Duct Burner for Small High Efficiency CCHP Systems	ALZETA Corp.	$94,880
Synthesis Gas/Hydrogen Fuel for Power Generation from Wheat Straw Utilization	Iowa State University	$95,000
Cost Reduction in Solar Cell Electricity by Replacement of Aluminum	Priyam, Inc.	$95,000
Innovative Design of High Solids Digestion Plants for Economic and Renewable Energy Production	Washington State University	$93,595
Hybrid DC and AC Linked Microgrids	University of Miami	$50,000
Determining the Feasibility of a High Temperature CO_2 Separation Membrane	Columbia University	$73,865

Dynamic Analysis Tool Development for Advanced Geometry Wind Turbine Blades	Scott Larwood	$67,250
Feasibility Evaluation of a Direct Carbon Fuel Cell Operating on Petroleum Coke Using Molten Carbonate Electrolyte	Gas Technology Institute	$94,906
The Next Wave in Air Conditioning: Acoustic Stirling Commercial Rooftop Units	CFIC-Qdrive	$86,762
Woven Turbo Wheel as Key Technology for Economical Compact and High Efficient R718 Chiller that Uses only Water as Refrigerant	Michigan State University	$95,000
High Efficiency and Low Cost Single Phase PFC Converters	Rensselaer Polytechnic Institute	$94,210
Feasibility Study of a Symmetrical Flexible Turbine Blade for Wind Energy Conversion	San Diego State University	$94, 856
Fanless Cooling System for Servers and Storage Systems	Clustered Systems Company, Inc.	$95,000
Residential Sub-Wetbulb Evaporative Chiller System	Nexajoule, Inc.	$95,000
Residential Utility Monitoring System Hardware Development	Desert Research Institute	$95,000
UV Photodecomposition of Siloxane	GC Environmental, Inc.	$92,354
Evaluation of a CO2 Mitigation Option for California Coastal Power Plants	University of California, Santa Cruz	$75,000
Residential Integrated Ventilation Energy Controller	EPB Consulting Group	$89,856

Feasibility Analysis of Cleanroom Airflow Reduction Based on Establishment of Theoretical Basis and Required Validation	Engsysco, Inc.	$95,000
Carbon Molecular Sieve with Tunable Properties	University of Southern California	$95,000
Solar Thermal Heat Pump/Chiller	Energy Conepts, Co. LLC	$95,000
Testbed Design for Gas Turbine Exhaust Pressure Recovery	Meruit,Inc.	$49,750
High Efficiency Heat and Power System for CCHP Applications	Altex TechnologiesCorp.	$94,915
Highly Efficient Production of Electricity and Syngas Using a Natural Gas Fuel Cell	Functional Coating Technology, LLC	$94,998
Feasibility Assessment of Operating Gas Engines on Alternative Gas Fuels	Colorado State University	$95,000
A Pore Flow Reactor for Landfill Gas Clean-Up	University of Southern California	$95,000
Enabling the Thermochemical Production of Hydrogen from Water: Investigation of the Bunsen Reaction in a Low Vapor Pressure Solvent	Oregon State University	$95,000

CHAPTER 2:
2006 Independent Assessment Reports

The Energy Innovations Small Grant (EISG) program awards numerous grants for innovative energy research projects every year. Independent Assessment Reports (IARs) highlight the project outcomes for each of the EISG projects. This chapter includes the IARs from grant projects that were awarded in 2006 that have not previously been published.

2.1 Electric Service Reliability Analysis Tool

Awardee: Angela Chuang

Principal Investigator: Angela Chuang

2.1.1 Abstract

The goal of this project was to determine the feasibility of an innovative method of using publicly available wholesale market information for advance assessment of system reliability needs to improve demand side responsiveness. The electric service reliability analysis tool was designed as a web based software application that relies on real time and day ahead forward market usage information which the researchers were able to download free of charge from publicly available data stores.

At the wholesale level, system reliability costs are allocated to wholesale electricity buyers distinct from energy costs. One of the reliability costs is imbalance energy, the difference between energy scheduled and energy actually used or generated. This information was used to calculate beta, the percentage of total energy procured in real time as imbalance energy. Beta values greater than 5.0 percent are considered abnormally high, based on the California electricity market design assumption that the total energy procured in real time will not exceed 5.0 percent of total energy.

In all sample periods tested the reliability tool was able to accurately detect critical peak periods by comparing calculated beta values with actual operating reserve. The researchers successfully prototyped the tool and were able to perform automated and manual data downloads, which included features for error trapping and recovery of missing data. The prototype interface, which included conditional alerts based on electricity usage and automated notifications, was found to be error free and capable of operating continuously for 120 hours.

Keywords: Electric service reliability, reliability analysis tool, reliability assessment, demand side responsiveness, demand response, wholesale market information, reliability cost

2.1.2 Introduction

Wholesale electricity costs are comprised of both reliability costs and energy costs. Although the assessed energy cost remains generally consistent with gradual increases over time, the assessed reliability cost varies greatly as a function of system capacity. The California electricity market was originally designed under the assumption that the total energy procured in real time would not exceed 3 percent to 5 percent. As the actual usage approaches this threshold and operating

reserves are depleted, emergency alerts are issued. Consequently, wholesale buyers are charged a reliability premium. Table 1 includes both reliability and energy cost components for the years 1998 through 2005, along with the number of emergency alerts issued for each year. A review of this information suggests that the California energy crisis in the early 2000s was a crisis of reliability, rather than purely energy.[1]

Table 1: Assessed Wholesale Reliability and Energy Costs Compared to Number of Emergency Alerts in California from 1998 to 2005

Year	Sys Load (GWh)	Assessed Reliability Cost (M$)	Assessed Energy Cost (M$)	ISO-Reported Total Electricity Cost (M$)	Number of Emergency Alerts
1998	169,241	849	4,702	4,914	12
1999	227,533	583	6,849	7,028	5
2000	237,542	17,904	9,177	25,769	92
2001	227,023	21,021	5,680	25,356	173
2002	232,010	261	9,804	9,901	3
2003	230,668	371	11,774	11,945	1
2004	239,788	396	11,453	11,665	1
2005	236,448	2,902	10,735	13,411	3

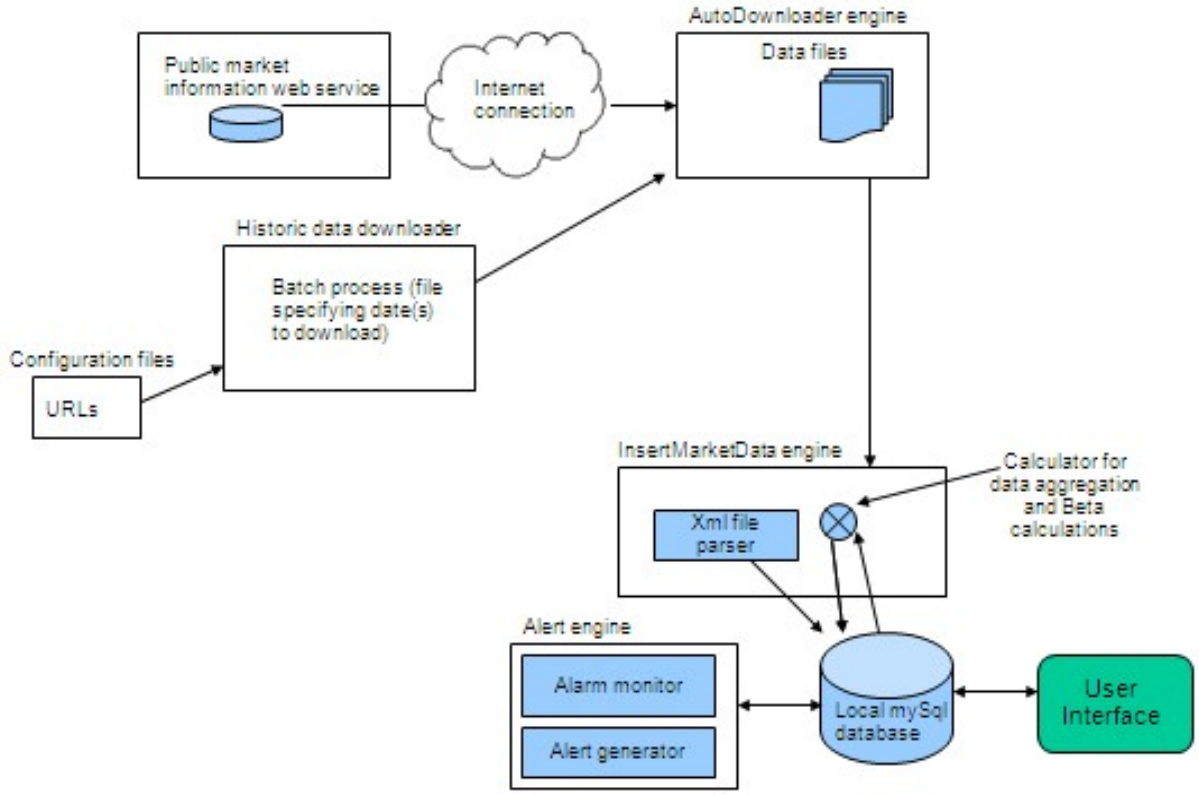
The researchers prototyped and tested a reliability analysis tool capable of issuing advance notification of pending emergency alerts to facilitate demand side response. Presently users are largely unaware of critical peak periods until they are billed for past usage. Given advance notice of critical peak periods in which system reliability is at risk and associated costs are high, energy retailers will have more time to adjust resource schedules and procurements and affect reliability cost reductions. The researchers suggested that demand side response to advance notification of critical peak periods could provide an increase in resource supply of 84.6 MW annually in California, valued at $2.4 million to the electricity consumer.

The reliability tool was designed as a web based, data base driven application capable of downloading publicly available usage data free of charge. Figure 1 shows the system

1 Chuang, A., "Assessing the Impact of Resource Availability on Electric Service Reliability Cost," *Electricity Journal*, March 2004.

architecture, which includes modules to automatically and manually download data from the California Independent System Operator (CAISO) server. This information is used to calculate beta, the percentage of total energy procured in real time as imbalance energy. Beta values greater than 5 percent are considered abnormally high, based on the California electricity market design assumption described above. The alert engine allows for user defined conditional alerts based on real time or day ahead usage data. Although the prototype development was limited for budgetary reasons, the researchers included requirements to provide scalability, flexibility, extensibility, security, maintainability, and speed using an open source platform. The prototype successfully identified all critical peak periods in the date ranges tested and operated without interruption or error for 120 hours.

Figure 1: Architecture Design for Reliability Analysis Tool



2.1.3 Objectives

The goal of this project was to determine the feasibility of an innovative method of using publicly available wholesale market information for advance assessment of system reliability needs to improve demand side responsiveness. The researchers established the following project objectives:

1. Verify that assessments of electric service reliability and costs available for years 2003 through 2005 match the trend in stage alerts issued by the CAISO and any deviations do not exceed 5 percent compared to prior years.
2. Demonstrate that the analysis method is capable of indicating critical peak hours within an error of +/-10 percent on sample critical peak days.
3. Confirm wholesale market information required is available at no charge. Confirm required information is available on day ahead and day of actual usage.
4. Confirm that specified functions and performance objectives can be achieved.
5. Verify design will accommodate day ahead and day of assessments within performance criteria.
6. Demonstrate data store matches public sources within two significant digits over a sample day.
7. Verify project goals are measurable using the test plan.
8. Demonstrate accuracy of tool within an error of +/-15 percent for indicating the top five critical peak hours in the imbalance energy market. Run tool continuously over 120 hours without failure.
9. Identify an application for the tool and assess associated benefits or cost savings.

2.1.4 Outcomes

1. The researchers collected and presented data for years 2003 through 2005 along with data previously collected for years 1998 through 2002. Reliability cost trends for recent years were consistent with those for prior years. An increase in the number of emergency alerts resulted in a corresponding increase in the assessed reliability cost. However the number of emergency alerts in recent years dramatically decreased, indicating that measures have been taken to avoid stage alerts. As a result, the researchers recommended that data analysis for years 1998 through 2002 be performed separately from the analysis for years 2003 through 2005. They calculated beta for the entire dataset. High beta values correlated with crisis events. Beta values consistently greater than 5 percent for January through December 2005 indicated that the system was able to operate closer to the margin without generating emergency alerts.
2. The researchers reviewed CAISO public market information to select the hour in each year ranging from 2003 to 2005 with the lowest reported actual operating reserve. For each of these critical peak days the researchers calculated the two day ahead and day ahead beta values. In all three cases both beta values exceeded 6 percent. These values were in excess of the design assumption used for the California electricity market, limiting real time energy procurement to a maximum of 3 percent to 5 percent.

3. The researchers identified data stores for wholesale market information that were publicly available and free of charge. Data needed to calculate beta could be obtained for real time, hour ending, hour ahead, day ahead, or two day ahead timeframes.

4. The researchers developed prototype requirements to allow for automated data download, storage, and calculations and to provide conditional alerts based on the calculated values. Although the prototype development was limited for budgetary reasons, they included requirements to provide scalability, flexibility, extensibility, security, maintainability, and speed using an open source platform. The researchers qualitatively confirmed through consultation with software developers that each of the prototype requirements was achievable.

5. Although a full implementation of the tool had web based architecture, the researchers designed the prototype to run on a single desktop PC. They uploaded day ahead, hour ahead, hour ending, and real time data into a MySQL database for use in calculation of beta. The user interface allowed conditional alerts based on reliability conditions and automated notification via email, FAX, pager, or phone.

6. The researchers compared original market source data to the database for every hour of one sample date. They detected no import errors.

7. The researchers drafted a test plan and schedule for the prototype, which included requirements for beta calculation accuracy, continuous performance for 120 hours, and detection of the top five critical peak hours during the testing period.

8. The data store was 100 percent accurate for all randomly selected sample days for either the automated or manual download. The prototype demonstrated the ability to recover from errors and retrieve missing data. The manual downloader experienced a connection time out issue with the public server, but was successful after a second attempt. The alert engine failed to run more than one day, but was redesigned to successfully run 120 hours without interruption. The tool was successful in identifying the top five critical peak hours for June through September, 2009.

9. Due to recent changes (April, 2009) in the electric system, the researchers were unable to order to ensure that a year's worth of data was available for analysis. The researchers deferred this task for future studies.

2.1.5 Conclusions

1. The researchers partially met the objective to verify that 2003 through 2005 data matched 1998 through 2002 reliability trends with no deviations exceeding 5 percent. The trends were consistent, but they were not quantified for comparison to the stated objective. However the researchers effectively demonstrated that changes in the power system in recent years warrant separate analysis of recent data from that previously analyzed.

2. The researchers met the objective to identify critical peak hours by calculating day ahead and two day ahead beta values for all sample critical peak days.

3. The researchers met the objective to confirm that wholesale market information is freely available on a day ahead and day of usage timeframe.
4. The researchers were able to meet the objective to confirm that the prototype requirements could be achieved, at least qualitatively. It was beyond the scope of this project to actually implement a robust application capable of satisfying all of the requirements.
5. The researchers met the objective to verify that the prototype design would accommodate day ahead and day of assessments within performance criteria.
6. The researchers met the objective to demonstrate accuracy in data upload into the tool.
7. The researchers met the objective to provide a testing plan that would ensure that project goals were achieved.
8. The researchers met or exceeded all performance objectives with no margin of error.
9. The researchers were unable to meet the project objective due to changes in the electric service market. This task will be completed as part of future research.

2.1.6 Recommendations

The researchers were able to achieve the project goal to prove feasibility of the electric service reliability assessment tool. Nearly all project objectives were met and many were exceeded. The prototype tool proved to be reliable and accurate in using publicly available data to identify critical peak periods for all date ranges tested.

As part of continued development of this technology, the Program Administrator recommends that the following tasks be completed:

1. Complete work on the last performance objective using data collected after April 2009.
2. Investigate alternatives for notification of critical peak periods to retail electricity buyers.
3. Survey retail buyers to assess their ability to react to the information provided by the tool and to affect change to their power usage. Verify the increase in resource supply that would result from advance notification of critical peak periods.
4. After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.
5. Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.1.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

1. Reduced environmental impacts of the California electricity supply, transmission, or distribution system
2. Increased public safety of the California electricity system
3. Increased reliability of the California electricity system
4. Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased reliability of the California electricity system. The researchers used a published method for quantifying real time response in competitive markets. They determined that rapid response to critical peak periods would result in an annual increase in resource supply of 84.6 MW for the State of California. Assuming an average critical peak price of $100/MWh, this increase is valued at $2.4 M per year.

2.1.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.1.8.1 Marketing/Connection to the Market

The researchers have not yet performed a complete market analysis. This technology would serve all consumer market segments of electricity buyers.

2.1.8.2 Engineering/Technical

The researchers will require collaboration for continued development of this technology. A full scale tool would require one to two years for development.

2.1.8.3 Legal/Contractual

The system software is protected by copyright.

2.1.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

Internet connectivity disruption may lead to delay in message delivery and demand response actuation. Reliability of the system will be addressed during system testing of the full scale tool.

2.1.8.5 Production Readiness/Commercialization

The researchers have not yet developed a commercialization plan and will need support to pursue commercialization.

2.2 Development of High Performance Magnesium Diboride Based Superconductor/Metal Matrix Composite Components for Use in Superconducting Fault Current Limiters

Awardee: Novē Technologies, Inc

Principal Investigator: Matthew J. Holcomb

2.2.1 Abstract

A goal of this project was to determine the feasibility of a new technique for fabrication of magnesium diboride based superconductor/metal matrix composite (SMMC™) components in superconducting fault current limiters (SCFCL). Mechanically and thermally robust, high performance superconducting materials and components will be critical to the development of economically viable utility grade SCFCLs. The SCFCL materials under study would operate at temperatures near 30 Kelvin. In this investigation the research team developed a mechanical milling process that provides for the synthesis of 50 gram quantities of SMMC™ powder that is greater than 99 percent phase pure and possesses a bulk superconducting transition temperature of approximately 38 Kelvin. This powder synthesis result was a necessary first step in the fabrication of bulk SCFCL components.

A second goal of the project was to develop a novel two powder co-deposition technique for SMMC™ powder and an insulating powder. A secondary part of this goal was to demonstrate a superconducting coil structure for a SCFCL component. This task involved the creation of a three dimensional (3D) structure of powder within a cold isostatic press mold prior to compressing the loosely packed material into a fully dense superconducting body. The investigation developed several prototype 3D powder filling systems based on the unique powder flow characteristics of the SMMC™ material. However the researchers did not demonstrate a viable coil fabrication technique by co-deposition of powders within the grant period. Instead the research team developed an alternate fabrication method in which the SMMC™ powder was compressed isostatically into grooves in an already formed insulating coil form. The latter method allowed for the fabrication of a mechanically and thermally robust bulk magnesium diboride based SMMC™ coil component. However the team did not answer questions about the scalability and commercial viability of this alternate technique.

Keywords: Fault current limiter, superconducting, magnesium diboride, mechanical milling, metal matrix

2.2.2 Introduction

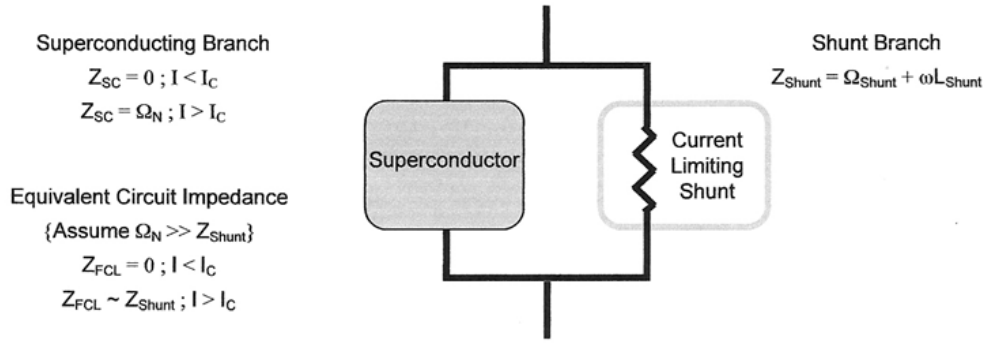
Power outages or blackouts are a serious concern for utilities and ratepayers. Outages arising from unplanned events such as lightning or downed power lines result in a large surge of current (or fault) being sent through the grid. Such faults can generate surge currents more than one hundred times the normal operating currents and can result in catastrophic damage to expensive grid connected equipment.[2] Utilities pay hundreds of millions of dollars each year to

2 http://www.superconductivitynewsupdate.com/newsletters/PDF/FaultCurrentLimitersOct2007.pdf

maintain and to add new circuit breakers and fuses to protect their transmission systems. Utilities can reduce or eliminate the cost of circuit breakers and fuses by installing fault current limiters (FCL). Benefits from FCLs include increased safety, reliability, and power quality. At the same time, FCLs also allow utilities to avoid or to delay upgrading existing circuit breakers and electrical substations to handle ever higher electrical surges. Fault currents in expensive transformers, for instance, can run 10 to 20 times the steady state design current, while FCLs can reduce these fault currents to levels not exceeding three to five times the steady state current, thus protecting and extending the life of transformers and associated utility equipment.[3]

Superconducting materials are an attractive option for FCLs in which a superconducting branch and a current limiting shunt are wired in parallel in the utility circuit, as shown schematically in Figure 2. In the absence of a fault condition, the superconducting branch carries all the current with negligible loss. When a high current fault condition occurs, the superconductor returns to the resistive normal state. The superconductor can operate near 65^0 K, minimizing cryogenic costs. The fault current is passively switched to the shunt. The shunt limits current magnitude to levels which are not damaging to other components in the circuit. The SCFCL is capable of automatic reset when the fault condition is removed. Recent attention in SCFCLs has been directed at new high temperature superconductors (HTS) with superconducting transition temperature greater than 77^0 K. However, high material costs of HTS superconductors have prevented their introduction into the marketplace for FCLs.

Figure 2: Schematic of a Generic Superconducting Fault Current Limiter (SCFCL)



If the cost of the superconductor materials could be lowered, the substantial benefits of FCLs would become available to utilities and ultimately to California ratepayers. A recent study estimated national costs of power outages and blackouts to be about $80 billion annually[4,5] and

3 http://www.superconductivitynewsupdate.com/newsletters/FaultCurrentLimitersOct2007web.htm

4 http://usgovinfo.about.com/od/consumerawareness/a/poweroutcosts.htm

the cost to the State of California to be about $8.1 billion.[6] Nationally, $57 billion (73 percent) was from losses in the commercial sector, and $20 billion (25 percent) was from losses in the industrial sector.[7] The study noted the reason for the commercial sector's high share of these costs was the large number of commercial sector customers, including small as well as large businesses, and the high cost per outage per customer. The industrial sector's cost per outage per customer was even higher, but there were only 1.6 million industrial customers compared to 14.9 million commercial customers. An estimate, assuming the same sector percentages in California as nationally, yields an estimate of $5.8 billion in losses in California's commercial sector and $2 billion in its industrial sector. While the balance attributable to the residential sector is only 2 percent of the total, it is difficult to estimate the value electricity customers place on uninterrupted service.[8] An important related concern is the risk to retention of California jobs in the industrial and commercial sectors that require high quality uninterrupted electrical power for their operations. It is clear that a lower cost high temperature superconducting material which leads to a lower cost superconducting fault current limiter could yield substantial benefits to both utilities and ratepayers.

In this project the advancement of science or technology that was proposed was the development of a new composite superconducting material based on magnesium diboride (MgB_2). This recently discovered superconductor has a superconducting transition temperature near 40^0 K, allowing operation at 30^0 K. While not as high a temperature as the HTS materials, MgB_2 is less complex and potentially much cheaper. The researchers found MgB_2 powder can be co-milled with gallium (Ga) powder (MgB_2/Ga SMMC™) and isostatically pressed into bulk shapes which have good superconducting properties without further heat treatment. Significantly, this material was found to have a critical current density greater than 5,000 a/cm^2 at 27^0 K, holding out the possibility of inexpensive fabrication of shapes suitable for FCLs. The researchers proposed a fabrication technique consisting of simultaneous deposition from two powder streams (Figure 3), one a mixture of MgB_2 and Ga powders and the second an inexpensive insulating powder such as alumina. During deposition the cold isostatic press (CIP) mold rotated under the two powder streams and was slowly lowered, producing two offset helical spirals of material, one conducting and one electrically insulating. After deposition the researchers compressed the mold at high pressure (about 50,000 psi) to produce a free standing helical winding test article with adjacent conducting windings insulated from each other. In this investigation the researchers proposed to fabricate a coil about two inches in diameter and several inches long with a conductor length of one meter.

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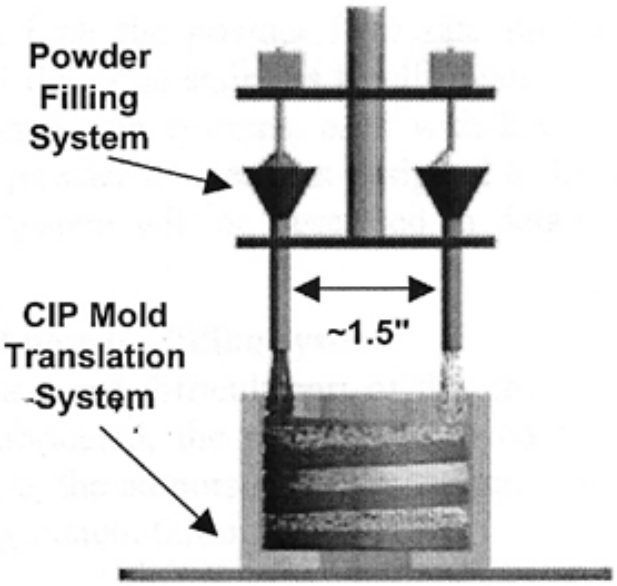
5 http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V2S-4JN2NPP-1&_user=4429&_rdoc=1&_fmt=&_orig=search&_sort=d&view=c&_acct=C000059602&_version=1&_urlVersion=0&_userid=4429&md5=075ea313a866db4fd13f7239cea508c4

6 http://certs.lbl.gov/pdf/55718.pdf

7 http://usgovinfo.about.com/od/consumerawareness/a/poweroutcosts.htm

8 http://usgovinfo.about.com/od/consumerawareness/a/poweroutcosts.htm

Figure 3: Two Powder 3D Powder Filling Concept



2.2.3 Objectives

The goal of this project was to determine the feasibility of fabricating high performance bulk MgB_2-based superconductor/metal matrix composite (SMMC) components for use in superconducting fault current limiters operating at temperatures below 30^0 K. The researchers established the following project objectives:

Synthesize high purity MgB_2/Ga SMMC™ powder. Refine mechanical milling procedures to increase SMMC™ batch size to 50 g quantities. Verify powder purity of greater than 99 percent by X-ray diffraction. Verify the bulk superconducting critical temperature in excess of 30 ^{O}K by zero field cooled DC magnetic susceptibility measurements.

Finalize design of a 3D one powder filling system. Measure powder deposition rates by timed powder depositions into an acrylic mold. Use the results to design a two powder filling system.

Fabricate the 3D two powder filling system. Demonstrate plus or minus 10 percent powder mass flow control with timed powder depositions into an acrylic mold. Verify visually the fabrication of a 3D coils structure using SMMC™ powder and an insulating powder in an acrylic test mold.

Fabricate bulk MgB_2/Ga coils. Demonstrate over one meter path length of the MgB_2/Ga portion of the coil component. Verify the resistance of the coil to plus or minus 10 percent of the theoretical value using four point resistance measurements at 300 ^{O}K and 77 ^{O}K. Demonstrate less than 10 percent variation in the filament cross sectional area of the bulk MgB_2/Ga coil.

Confirm visually the absence of thermal stress fractures in the bulk MgB_2/Ga coil after 10 thermal cycles from 300 ^{O}K to 77 ^{O}K.

2.2.4 Outcomes

The researchers prepared 50 g batches of high purity MgB_2/Ga SMMC™ powder using an 80 ml tungsten carbide (WC) milling vial and a planetary mill. The optimum mechanical milling conditions were obtained using two 25 mm diameter balls, five 10 mm diameter WC balls, and 0.1 ml of anhydrous methanol as a process control agent. The researchers confirmed phase purity of the prepared MgB_2/Ga SMMC™ to be in excess of 99 percent by in house powder X-ray diffraction. They measured the bulk superconducting transition temperature of the prepared MgB_2/Ga SMMC™ at 38 ^{O}K by zero field cooled magnetic susceptibility.

The researchers designed and fabricated a 3D one powder filling system using commercial components. They found the powder had to be fluidized by vibration to achieve uniform deposition rates. Run to run overall powder deposition rates varied by plus or minus 0.8 percent in separate timed depositions of 20 g of MgB_2/Ga SMMC™ powder into an acrylic mold. However the deposition rate within a given test run was not constant due to excessive funnel size.

The researchers designed and fabricated a custom 3D two powder deposition system based on glass hoppers. As in the prototype version, it was necessary to fluidize the powder to achieve consistent flow. Powder fluidization, while beneficial to powder flow, caused the powder to move through the auger driven system even when the auger was stationary. They concluded this two powder deposition approach was unsuitable for coil fabrication during the grant period.

Late in the project the researchers developed an alternate method to fabricate a bulk MgB_2/Ga component. They machined a cylindrical coil former with a seven turn helical groove pattern out of insulating material. The coil former was inserted into the mold, and the SMMC™ powder loaded into the mold on a vibration stage in a dry box. The vibration allowed the SMMC™ powder to flow more completely into the grooved coil pattern. After sealing, the researchers placed the mold in the cold isostatic press (CIP) and compressed it at 50,000 psi for 15 minutes. Following compression, they removed excess powder from the coil former surface by machining, leaving the material in the grooves which comprised a seven turn coil of filament 0.8 m in length. The surface finish of the coil was not uniform and was pitted with sections where the composite had clearly broken off. The coil, however, was mechanically and thermally robust and showed no visual degradation on thermal cycling between 300 ^{O}K and 77 ^{O}K. The researchers determined the MgB_2/Ga SMMC™ coil resistance was 0.56 milliohms at 77 ^{O}K by four point probe resistance measurements.

2.2.5 Conclusions

The researchers successfully synthesized high purity MgB_2/Ga SMMC™ powder in 50 g quantities. They met the objective of verified powder purity of greater than 99 percent and a bulk superconducting critical temperature in excess of 30 ^{O}K.

The researchers met the objective of consistent average deposition rates from run to run. However the deposition rate within a given deposition run was too variable for the apparatus design to be viable. Thus they did not meet this objective.

Because reproducible flow rates were not achieved, the researchers concluded this was not a viable technique and the steady state powder deposition approach was abandoned.

The researchers came close to meeting this objective, but questions remain about the practicality of the approach.

The alternate approach to fabricate a prototype MgB_2/Ga SMMC™ coil using a novel coil former and a cold isostatic press did produce a test article. The researchers did not have time to fully characterize this component. The alternate technique may be scalable, but costs for this method could be very high.

Although this research did not prove feasibility of the intended approach, the researchers made significant strides in scaling up powder quantities to 50 g batches. This success makes it possible to work with bulk quantities of the superconducting material.

2.2.6 Recommendations

The researchers identified three key engineering issues to be solved:

1. powder flow rate control
2. powder flow pattern
3. powder layer morphology within the cold isostatic press mold

The researchers discovered the fluidization and transport of powders depend critically on the atmosphere (argon or vacuum) and the nature of the mechanical motion of the vibration device. These discoveries led them to conclude that the flow of powder may be controlled by simple valves rather than a driven auger system. These developments should be pursued to achieve a consistent powder feed system.

2.2.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

1. Reduced environmental impacts of the California electricity supply, transmission, or distribution system
2. Increased public safety of the California electricity system
3. Increased reliability of the California electricity system
4. Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased reliability of the California electricity system. If the issue of cost of the superconductor in higher temperature SCFCLs could be solved, substantial savings would accrue to the utility and ultimately the ratepayer. A

recent study estimated power outages and blackouts cost California an estimated $8.1 billion.9 The bulk of this cost occurs in the commercial and industrial sectors. While the sector balance attributable to residential sector is only 2 percent of the total, or $160 million, it is more difficult to estimate the value electricity customers place on uninterrupted service.10 An important related concern is the risk to retention of high paying California jobs in businesses in the industrial and commercial sectors requiring high quality uninterrupted electrical power.

2.2.8 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which included all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.2.8.1 Marketing/Connection to the Market

The path from the laboratory tests described in this project and a marketable product is very long. The researchers should contact market players only to determine product engineering requirements until more significant progress is made in the laboratory.

2.2.8.2 Engineering/Technical

Some post project engineering work is described in the Recommendations section above.

2.2.8.3 Legal/Contractual

The researchers did not describe any patent activity.

2.2.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

These assessments can be delayed until the researchers have proven the feasibility of a manufacturing process.

2.2.8.5 Production Readiness/Commercialization

Prior to commercialization studies the researchers must prove feasibility of a commercially viable fabrication technique.

2.3 Development of an Ordered Thin Film Palladium Alloy Membrane for Hydrogen Separation

Awardee: ITN Energy Systems

Principal Investigator: Bruce Lanning

2.3.1 Abstract

The objective of this project was to demonstrate feasibility of a new fabrication technique for free standing thin film membranes that exhibit high hydrogen flux, superior resistance to poisoning, and stability under thermal cycling. There were two main technical goals: to fabricate a free standing metal film membrane of five micron thickness and to demonstrate a

9 http://certs.lbl.gov/pdf/55718.pdf

10 http://usgovinfo.about.com/od/consumerawareness/a/poweroutcosts.htm

hydrogen flux through the membrane of 200 standard cubic feet per hour per square foot (scfh/ft^2) at 20 psi pressure difference across the membrane. The researchers used deposition of thin defect free metal films by sputtering and evaporation techniques onto treated silicon wafers to fabricate the membrane. A special oxidation pre-treatment of the wafers allowed release of the deposited films from the silicon wafers. The researchers used membrane materials palladium (Pd) based and vanadium (V) based alloys. Tests produced mixed results for obtaining free standing films released from silicon wafers, particularly in the case of vanadium. Consequently the researchers fabricated thicker composite test specimens from 10 micron thick palladium foils made by electroless plating and 25 micron thick vanadium foils made by rolling. The palladium foils were coated with thin vanadium deposited films and the vanadium foils with thin palladium films. Testing a Pd/V foil/Pd sandwich structure for about 50 hours at 648 ^{O}K yielded a measured hydrogen flux rate of 40 scfh/ft^2. This result fell short of the goal. At 723 ^{O}K the composite Pd/V foil/Pd membrane did have a hydrogen flux rate greater than a palladium sample of half the thickness. The project did not meet the goals of free standing film thickness and hydrogen flux rate. Based on the lessons learned from releasing films from silicon wafer substrates, the researchers concluded that a new generation of separation membrane with Group VB alloys could be scaled into manufacturing in future development efforts.

Keywords: Hydrogen separation, permeable, membrane, composite, thin film, vanadium, sputtering, evaporation

2.3.2 Introduction

This project involved a new hydrogen fuel production technology for environmentally preferred advanced generation (EPAG). Pure hydrogen as a fuel has many desirable features including more benign emissions[11] compared to hydrocarbon fuels and higher energy content per unit weight. Hydrogen is an energy carrier in such applications rather than a primary energy source since it is almost always present in nature in a chemically combined state. When hydrogen is extracted it is present in an admixture of other gases and impurities. This is significant since hydrogen powered fuel cells, of current interest in distributed generation and transportation, are sensitive to impurities.[12] Therefore a low cost, efficient method to separate hydrogen from other gases is needed.

Hydrogen separation is a large scale challenge. World production of hydrogen is 42 million tons per year of which 48 percent is produced from natural gas, 30 percent from oil, 18 percent from coal, and 4 percent from electrolysis.[13] In the US nine million tons of hydrogen are produced per year. Ninety-five percent of this is the result of steam reforming of natural gas.[14] Hydrogen is used in the metallurgical industry to obtain reducing environments; in the chemical,

11 www-formal.stanford.edu/jmc/progress/hydrogen.html

12 www.hydrogen.energy.gov/fuel_cells.html

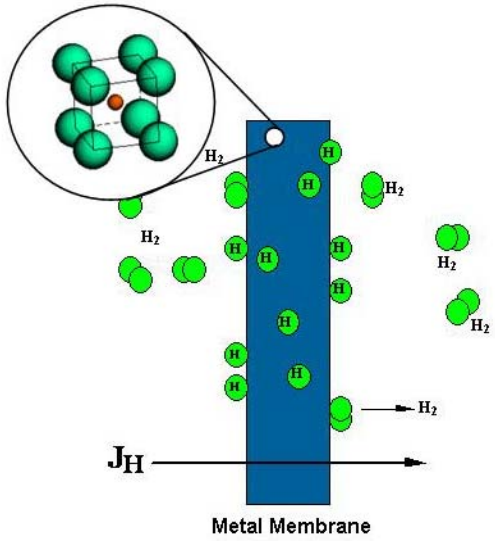
13 www.hydrogenassociation.org/general/faqs.asp#howmuchproduced

14 www.hydrogenassociation.org/general/factSheet_production.pdf

pharmaceutical, and petroleum industry as a raw material; and in the glass, ceramics, food, and electronics industries.[15] Nine million tons of hydrogen would be enough to power five to eight million homes or fuel 20 to 30 million hydrogen powered cars.[15]

A number of extraction techniques have been applied. In all of them hydrogen must be separated from significant amounts of other gases. The technique for producing the purest hydrogen is to diffuse it through a hydrogen selective permeable membrane filter composed of palladium or a palladium alloy (Figure 4). However palladium is a relatively expensive metal, $247 per ounce in June 2009.[16] Commercially available palladium based filters are relatively robust with tube walls about 100 microns thick. To reduce cost, the palladium

Figure 4: Schematic of Metal Membrane for Hydrogen Separation Only Hydrogen Is Able To Pass Through the Membrane.



membrane could be thinner or the membrane filter could be constructed of less costly material. The resulting benefits to the California ratepayer of a less costly filter would be greater availability of low cost, low emissions fuel cells in the distributed generation and transportation markets.

The advancement of science proposed in this project was the development of much thinner palladium or palladium alloy membranes. The alloys included copper and silver. The researchers established a palladium alloy thickness goal of five microns. That thickness would greatly reduce the material cost for palladium and would greatly increase hydrogen diffusion

15 www.uigi.com/hydrogen.html

16 http://palladiumprice.org/

rates through the filter. The researchers also considered new membrane materials such as vanadium, niobium, and tantalum which are known to absorb large amounts of hydrogen and which have a more open crystal (body centered cubic) structure, giving higher hydrogen diffusion rates.

2.3.3 Objectives

The goal of this project was to determine the feasibility of new robust thin film palladium alloy membranes, such as ordered β Pd-Cu alloys, that exhibit high hydrogen flux, superior resistance to sulfur poisoning, and stability under thermal cycling. The technology was based on the controlled formation of thin, defect free, palladium alloy films using vacuum processing methods that can be scaled up. The researchers established the following project objectives:

1. Conduct a trade study to identify optimal binary and ternary alloys based on first principles and published measurements. Focus on those that deliver enhanced hydrogen permeability and sufficient mechanical integrity under thermal cycling. Select alloys that optimize permeation and mechanical stability.

2. Develop robust processing parameters for the fabrication of free standing thin membranes of the selected materials less than five microns thick using ion assisted vacuum methods. Demonstrate the fabrication of a free standing, pinhole free palladium alloy membrane that is less than five microns thick. Fabrication should not require a clean room.

3. Demonstrate the efficacy of the hydrogen membranes operating in the presence of sulfur. Test and evaluate the efficacy of separating pure hydrogen (more than 99.995 percent) from a dilute hydrogen stream containing sulfur impurities. Demonstrate a new palladium alloy membrane with hydrogen flux of 200 standard cubic feet per hour per square foot (scfh/ft^2) at 20 psi differential pressure through a freestanding membrane in the presence of 10 ppm of hydrogen sulfide. Demonstrate 100 thermal cycles with less that 1 percent degradation in membrane performance.

4. Perform an economic evaluation for different alloy structures. Write a business plan to commercialize the technology.

2.3.4 Outcomes

1. The researchers successfully conducted a literature study to identify optimal binary and ternary alloys. They identified materials criteria for optimum hydrogen permeation and mechanical stability.

2. The researchers fabricated a variety of thin film membranes using different processes. They did not produce five micron films of vanadium palladium alloys because of mechanical instabilities.

3. The researchers tested a Pd/V foil/Pd sandwich structure membrane for approximately 50 hours at 648° K and measured flux of 20 SCCM/cm^2 (equivalent to 40 scfh/ft^2). They also tested a membrane at 623, 673, and 723 ^{O}K. In comparison to a pure palladium membrane of half the thickness, the Pd/V foil/Pd composite had a greater flux at 723° K.

The researchers tested the membrane to failure. Analysis of the failure results indicated embrittlement as the cause of failure. There is no evidence the researchers conducted hydrogen permeability tests in the presence of 10 ppm hydrogen sulfide.

4. The researchers performed a preliminary economic analysis for commercialization of this membrane technology. The results showed thin vanadium/palladium foils are able to yield high hydrogen fluxes with greater than 99.999 percent purity. However membranes must be less than five microns thick to meet the cost requirements for hydrogen refueling stations.

2.3.5 Conclusions

1. The researchers met this objective.
2. The researchers did not demonstrate fabrication of a free standing, pinhole free palladium alloy membrane less than five microns thick.
3. The researchers did not demonstrate a membrane with hydrogen flux 200 scfh/ft^2 at 20 psi through a freestanding membrane. They did not attempt the goal of demonstrating 100 thermal cycles with less that 1 percent degradation in membrane performance.
4. The researchers did not complete the economic evaluation and plan for scale up and commercialization of this membrane technology because the technical objectives were not met.

The researchers performed credible research in the area of hydrogen purification membranes. However they did not meet two main objectives of the project: to fabricate robust thin films less than five microns thick and to demonstrate membranes that exhibit high hydrogen flux, superior resistance to sulfur poisoning, and stability under thermal cycling.

2.3.6 Recommendations

Prior to subsequent development of thin film membranes, the Program Administrator recommends the researchers should:

1. Conduct quantitative calculations of hydrogen flux with known experimental data of elemental palladium, its alloys, and vanadium as a function of thickness.
2. Estimate membrane thickness to achieve the flux goal of 200 scfh/ft^2 at 20 psi.
3. Conduct a stress analysis of thin palladium or vanadium alloy films with a pressure differential of 20 psi as a function of diameter and film thickness.
4. Conduct an experimental micrographic demonstration on such films to demonstrate performance under approximate operating conditions.

2.3.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

1. Reduced environmental impacts of the California electricity supply, transmission, or distribution system
2. Increased public safety of the California electricity system
3. Increased reliability of the California electricity system
4. Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California electricity supply, transmission, and distribution system. Pure hydrogen can have desirable features when it is burned in air as a fuel [17] if proper care is taken not to produce excessive oxides of nitrogen. Hydrogen is an energy carrier in such applications rather than a primary energy source. When hydrogen is extracted from natural sources it is present with other gases and impurities. Fuel cells, in particular, require that the impurities be removed to prevent degradation of the fuel cell. Other prime movers also require the removal of sulfur compounds. Successful development of a hydrogen separation membrane could greatly reduce the cost of providing relatively pure hydrogen to these electricity generation devices. No benefits can be estimated until a technically successful membrane has been fabricated and tested.

2.3.8 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.3.8.1 Marketing/Connection to the Market

There is no evidence of marketing efforts relevant to this project.

2.3.8.2 Engineering/Technical

There is no evidence of any new engineering or technical information that is relevant to this project.

2.3.8.3 Legal/Contractual

No patents had been applied for.

2.3.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

It is premature to develop risk assessment/quality plans since technical feasibility has not yet been firmly established.

2.3.8.5 Production Readiness/Commercialization

It is premature to consider commercialization plans.

17 http://www-formal.stanford.edu/jmc/progress/hydrogen.html

2.4 Ultra Low NOx Duct Burner for Small High Efficiency CCHP Systems

Awardee: ALZETA Corp.

Principal Investigator: Bob Nickeson

2.4.1 Abstract

Due to NO_x emissions, conventional duct burners are incompatible with clean burning, natural gas fired prime movers without utilizing stack gas treatment. This is particularly true for small distributed generation combined heat and power plants (DG CCHP) since the implementation of strict new California Air Resources Board (CARB) 2007 emissions standards. This project showed the feasibility of an ultra low emissions duct burner for small and micro turbine based heat recovery steam boilers. The benefits of this burner in a CCHP unit include near package steam boiler thermal efficiencies, emissions better than CARB 2007 requirements, and no need for stack gas treatment. The project utilized a turbine exhaust gas generator (TEGG) burner, or turbine exhaust simulator, which produces flue gas upstream of the duct burner. This simulated exhaust gas flow was sized to match that of a 150 KW microturbine. The test rig results demonstrated the possibility of an overall system efficiency of 75 percent which was 35 percent greater than the stand alone microturbine efficiency. The NO_x emissions were measured at less than 0.07 lb per MWhr which was the equivalent of 2.3 ppm (parts per million) corrected to 15 percent oxygen (O_2), while maintaining carbon monoxide emissions of 0.1 lb/per Whr (less than 4.3 ppm at 15 percent O_2). The duct burner test apparatus achieved turndown levels of 1.5 to 1.0. Preliminary production cost projections for the burner were $12,000. The researchers estimated modest adaptation of this technology would increase the penetration of small DG CCHP systems in the Southern California area by 115 MW. The increased use of DG CCHP could result in savings to California cogeneration plant operators of $215 million in reduced cost of electrical generation over the initial five year period. The larger picture for the potential for DG CCHP systems less than 20 MW was reported by a 2007 California Energy Commission Staff Report.[18] These systems have the potential for growth from under 1000 MW in 2005 to over 3000 MW in 2020, as long as the strict 2007 CARB emissions levels can be met.

Keywords: Duct burners, supplemental burners, cogeneration, low NO_x burners, ultra low NO_x burners, combined cooling heating and power (CCHP), greenhouse gases

2.4.2 Introduction

Combined heat and power (CHP) or combined cooling, heat, and power (CCHP) offer very high fuel utilization (75 percent to 85 percent). High fuel utilization reduces costs, regulated emissions, and carbon dioxide emission. There are several CHP installations in California above four megawatts. The potential use of CHP or CCHP is much higher for units smaller than four or five megawatts. Technology exists to implement CHP in this size range, but this technology does not necessarily meet California Air Resources Board 2007 air emissions standards for distributed generation and CHP. These standards require NO_x and carbon monoxide emissions

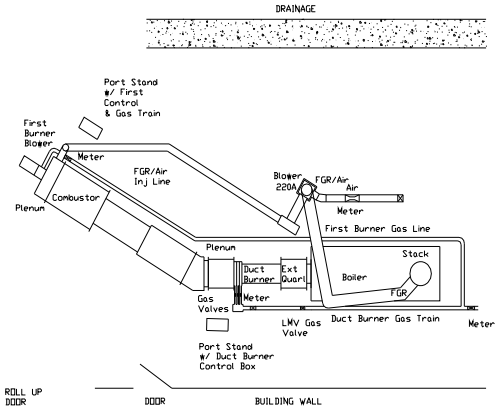
18 www.localpower.org/documents/reporto_cec_dgroadmap.pdf

to be on par with large, advanced central power plants. Some small gas turbine engines can meet these goals. However, to run in the CHP mode, it is often necessary to add a duct burner between the engine and the heat recovery boiler. The duct burner adds operational flexibility to meet the site needs by adding heat in varying amounts to the turbine exhaust. At the time this project was approved there was no duct burner that could meet the 2007 air emission standards suitable for the smaller turbines. Without a low emission duct burner CHP facilities either could not meet the air standards or they could not meet the economic needs of many sites that needed a duct burner in the energy system.

California ratepayers would benefit by having a technology for small scale energy systems that could allow additional steam heat while meeting and exceeding the California Air Resource Board (CARB) 2007 emission standards without expensive exhaust gas treatment. The overall potential is a threefold increase in installed capacity of CCHP systems of less than 20 MW by 2020.

The advancement of technology proposed in this project was an ultra low emissions duct burner for small turbine based cogeneration plants. This duct burner would allow small heat recovery steam boilers to achieve thermal efficiencies close to those of much larger plants while reducing air emissions below the CARB 2007 standards. In addition, it would be done without stack gas treatment. Companies such as Forney,[19] Coen,[20] and John Zink[21] offer low emission duct burners for large multi-megawatt applications, typically for rectangular cross section ducts. This project focused on smaller sub-megawatt micro-turbine systems with circular duct cross sections. The researchers designed, fabricated, and tested an ultra low NO_x duct burner that could work with a typical micro-turbine generator exhaust stream. Figure 5 shows a schematic of the duct burner and Figure 6 shows a photo of the test apparatus.

Figure 5: Schematic of Low-NOx Duct Burner



19 www.forneycorp.com/utcfs/ws-389/Assets/adVantageTechBull.pdf

20 www.coen.com/i_html/ductburn_gas.html

21 johnzink.com/products/burners/html_jz/burn_jz_lit.htm

Figure 6: Photo of Duct Burner Test Apparatus

2.4.3 Objectives

The goal of this project was to determine the feasibility of using a duct burner in the exhaust of small distributed generators such as micro-turbines to increase overall efficiency while meeting or surpassing CARB 2007 air emissions standards. The duct burner design was a downsized version of larger duct burners already in service so as to retain the desired combustion characteristics for efficiency and low NO_x and CO emissions. The researchers established the following project objectives:

1. Demonstrate potential increases in system efficiencies of 20 percent for a system that includes a 250 kW micro-turbine.
2. Demonstrate NO_x emissions at levels of 0.07 lb/MWhr or the equivalent of less than three parts per million corrected to 15 percent oxygen.
3. Demonstrate turndown capabilities of four to one.
4. Demonstrate a burner pressure drop of two inches water column or less.
5. Demonstrate burner durability and stability by operating at off design conditions 1 percent oxygen above and below the design flow stream oxygen conditions.
6. Demonstrate a production cost for the burner of $15,000 or less.

2.4.4 Outcomes

The outcomes from this project corresponding to the objectives above were the following:

1. The researchers reported system efficiency increases of 35 percent for the simulated micro-turbine exhaust duct burner packaged boiler combination. The researchers changed the proposed engine size from 250 kW to 150 kW due to limitations in the existing test burner rig.

2. The NO_x emissions levels from the duct burner were less than 0.07 lb/MWhr, achieving the equivalent of 2.3 ppm corrected to 15 percent O_2 at assumed pre-existing system efficiency levels. This was achieved while maintaining a rigorous 0.1 lb/MWhr CO emission level (sub 4.3 ppm at 15 percent O_2). To maintain this emissions level, especially the CO emissions, it was necessary to divert exhaust flow to the burner. CO emissions while firing only a portion of a constant flow were not successfully maintained at targeted performance levels.

3. Using the alternative turndown system that could constantly take all the exhaust flow from a turbine and achieve turndown by firing only a portion of the flow, the researchers achieved burner turndown levels of 1.5 to 1.0.

4. The apparatus achieved burner pressure drops of less than two inches water column in the tested operating range. However only 70 percent of full fire was demonstrated.

5. The researchers demonstrated the capability to safely operate the duct burner at off design conditions of 1.5 percent O_2 above and below the nominal oxidizer O_2 condition.

6. The researchers estimated preliminary production cost projections for the burner at $12,000.

2.4.5 Conclusions

The researchers made significant progress toward proving feasibility.

1. System efficiency increases of 35 percent and greater are possible with this technology. This goal was met.

2. The researchers met this very important goal. Accounting for the increased system efficiency factors, the effective emission levels were reduced even further. Reported emissions levels represent an 80 percent reduction from then current state of the art duct burner NO_x emissions performance for small engines.

3. Burner turndown levels were limited to 1.5 to 1. This did not meet program goals.

4. In the range of tested firing rates, burner pressure drop was within the maximum allowable range. However estimated drops at full fire were projected to be 15 percent above the targeted two inches water column maximum.

5. Safe operation of the burner at duct gas stream oxygen levels within the targeted range demonstrated burner durability and stability.

6. Burner production costs of $12,000 met the target cost goal of $15,000 or less.

Additional conclusions include:

7. The researcher achieved burner integration into the boiler.
8. The constant flow turndown (CFT) operational approach did not achieve required CO emission levels. It was necessary to use the diverted flow turndown (DFT) approach.
9. Test facility fan and gas flow capacity and heat loss constraints contributed to limiting high fire operation to 70 percent of full fire. This also limited the demonstrated turndown.
10. Uniform fuel gas and duct flow distribution are critical for good mixing and good emissions performance. In this project it was necessary to control the adiabatic flame temperatures to between 2500^0 F and 2700° F to meet both NO_x and CO emissions goals.

2.4.6 Recommendations

1. Conduct market analysis for small and micro-turbine based cogeneration opportunities, including an inventory of potential sites with existing or potentially compatible electric/thermal loads.
2. With micro-turbine and duct burner industry engineers, investigate the relative benefits of constant versus diverted flow turndown operation to determine if development of the former is worthwhile.
3. Refine burner design for simpler diverted flow turndown operation and/or the more complicated constant flow turndown operation for improved emissions, pressure drop, and turndown performance.
4. Demonstrate a full scale 65–150 kW system with a boiler.
5. Assess the opportunities for the project technology in larger scale industrial system applications. These applications may have a greater market potential to pursue than the micro-turbine based market.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.4.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

1. Reduced environmental impacts of the California electricity supply, transmission, or distribution system

2. Increased public safety of the California electricity system
3. Increased reliability of the California electricity system
4. Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is the increased affordability of electricity in California. This would be achieved by reducing the cost of co-generated electricity from small CCHP generators, particularly micro-turbines. Assuming a five year penetration period, the Program Administrator projects 46 MWh of energy could be saved by deployment of this technology. This is equal to savings of 4.7 billion cubic feet (bcf) of gas and $110 million. Electric energy cost savings to California cogeneration plant operators could be $215 million over the period. Furthermore, the system efficiency enhancements could reduce emissions of NO_x by 735 tons and CO_2 emissions by 808 thousand tons over the five year period. Large sale system opportunities could greatly expand the potential benefits.

2.4.8 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.4.8.1 Marketing/Connection to the Market

A California Energy Commission report[1] on projected applications of distributed generation combined heat and power systems up to 20 MW shows a larger market by 2020. This report predicts an additional 2000 MW of installed capacity between 2005 and 2020. The technology described in this report could play a large part in the increased use of CCHP systems.

2.4.8.2 Engineering/Technical

The researchers are seeking additional funding to complete full size testing on real engine systems.

2.4.8.3 Legal/Contractual

The researchers reported no post project activity in this area.

2.4.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

The researchers did not report any new items in this area.

2.4.8.5 Production Readiness/Commercialization

It is too early to prepare commercialization plans.

2.5 Synthesis Gas/Hydrogen Fuel for Power Generation from Wheat Straw Utilization

Awardee: Iowa State University

Principal Investigator: Justinus A. Satrio

2.5.1 Abstract

This project focused on the development and demonstration of a new process that could produce either synthesis gas (syngas) or almost pure (greater than 98 percent) hydrogen from wheat straw feedstock. Syngas or hydrogen produced by this technique could be used as a supplemental fuel for California's natural gas electric generation power plants or fuel cells. This renewable, predictable, and reliable alternative energy source could help offset the use of natural gas for the generation of electricity and help California utilities meet aggressive Renewable Portfolio Standard (RPS) goals without the need for major plant modifications.

There are two keys to success regarding this approach: overcoming the inherent challenges of high lignin content and high inorganic (mineral) content of wheat straw to produce low lignin bio-oil that can feed a steam reformer and producing a consistent blend of high quality syngas or almost pure hydrogen using advanced steam reforming techniques. Low lignin bio-oil can be produced by using a fast pyrolysis reactor system equipped with a multiple stage condensation unit. Low lignum bio-oil can then be easily reformed into syngas and hydrogen using both conventional and advanced reformation techniques.

Researchers collected, cleaned, and processed wheat straw using a fast pyrolysis reactor system with fractionating condenser unit, yielding multiple bio-oil fractions with low amounts of lignin and char. High lignin content bio-oil residues can either be burned off to provide heat required by the system or be used as feedstock for producing value added chemicals. Similarly, the char can be used as a fuel for an industrial process, sold to manufacturers of activated carbon, or injected back into the soil as soil enrichment with the benefits of carbon sequestration. Low lignin bio-oil produced by the pyrolysis reactor can be transported by tanker truck to a nearby natural gas power generating facility where it can be fed into a steam reformer that produces synthesis gas (syngas). The syngas can be injected into the steam generator of the power plant, thus offsetting the use of natural gas. Alternatively, the bio-oil can be transported to a distributed generation facility where it can be reformed to almost pure hydrogen using conventional or advanced steam reformation techniques for the purpose of operating a fuel cell.

Although this project successfully demonstrated the proof of concept, additional research is needed before it can be commercialized. Development of new and improved catalysts, further investigation of steam/carbon ratios on product yields, evaluation of bio-oil reforming at different temperatures, optimization of the advanced steam reforming reactor developed at Iowa State University (ISU), investigation of gasification techniques to produce synthesis gas as an alternative approach to catalyst based steam reformation systems, testing of the system in fluidized bed mode, and determination of the technical and economic feasibility of the proposed process technology at commercial scale are all needed for commercialization.

Keywords: Bio-oil, fast pyrolysis, steam reforming, gasification, power generation, biomass, wheat straw

2.5.2 Introduction

California's three largest utilities – Southern California Edison, Pacific Gas and Electric, and San Diego Gas and Electric – collectively served 18 percent of their 2010 retail electricity sales with

renewable power. These utilities are targeting 33 percent of all retail electricity sales to come from renewable power sources by 2020.[22] New, cost effective renewable technologies and concepts are essential to meet the challenging 33 percent Renewable Procurement Standard (RPS) goal in California.

The purpose of this project was to develop a renewable, stable, and reliable alternative energy resource that could either supplement or substitute the use of natural gas for the production of electricity without requiring major plant modifications. In 2005 the production of electricity in California was 289 GWh, of which 40 percent was produced by using natural gas. Natural gas prices have experienced volatility in the past. For instance, between June 2005 and May 2006 the price of natural gas fluctuated between $6 and $15 per MMBTU. Natural gas price uncertainty can have an adverse economic impact on California's electricity ratepayers as well as owners of distributed generation power systems (e.g., fuel cells) located at customer facilities. Although the price of natural gas supplies has stabilized recently due to the discovery of shale gas, price volatility could return if the extraction process for shale gas proves more difficult than anticipated. A preferred option would be to supplement the use of natural gas with a clean source of syngas or hydrogen fuel for central and distributed power applications.

The research team demonstrated a process that can produce either synthesis gas (syngas) or almost pure hydrogen from wheat straw feedstock. Syngas can be used as a supplemental fuel for California's natural gas electric power generating plants. Hydrogen can be used for fuel cells in a distributed generation configuration. This renewable, stable, and reliable alternative energy source could help offset the use of natural gas for the generation of electricity without the need for major plant modifications and thus help California meet its aggressive 2020 RPS target of 33 percent.

Investigators initially considered two sources of straw for this concept, wheat and rice, which are both abundant resources in California. Wheat straw production is approximately 400,000 tons per year and rice straw is approximately 300,000 tons per year. The researchers selected wheat straw as the feedstock of choice since its properties are more favorable for the proposed process. In this system wheat straw is collected and preprocessed to yield bio-oils and porous char by using a fast pyrolysis reactor system equipped with a multiple stage condensation unit. The condensation unit allows bio-oils to be collected in different fractions (e.g., low and high lignin content). It is important to maximize the yield of low lignin bio-oil since it has considerably greater market value than high lignin bio-oil. Once produced, low lignin oil could be transported from the processing facility by tanker truck to a natural gas electric power generating plant where it would be fed into a steam reformer to produce syngas. The syngas would then be injected into the steam generator of the power plant, offsetting the use of natural gas. Figure 7 illustrates a simplified process flow chart.

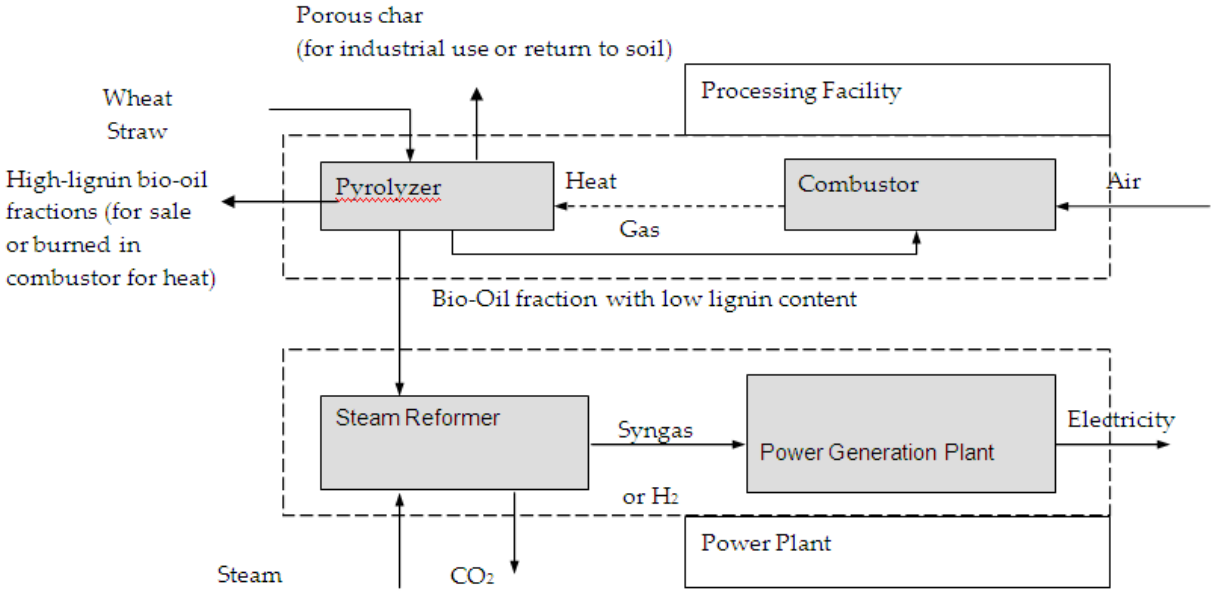
22 Former California Governor Arnold Schwarzenegger signed Executive Order (EO) S-21-09 on September 15, 2009, directing the California Air Resources Board (CARB) to adopt regulations requiring 33 percent of electricity sold in the state come from renewable energy by 2020.

Alternatively, the low lignin bio-oil can be reformed to pure hydrogen by using core-in-shell combined catalyst/sorbent technology developed at Iowa State University (ISU) as a feedstock for fuel cells in a distributed generation configuration. Limited testing of the advanced ISU reformer achieved at least 98 percent pure hydrogen suitable for many fuel cell applications.

Less desirable high lignin bio-oil can be used as a combustion fuel to provide heat required by the system or as feedstock for producing other valued chemicals. The porous char by-product is easily portable and can be used as a combustion fuel for an industrial process, sold for making activated carbon, or injected back into the soil for enriching the soil and providing a means of carbon sequestration.

The use of biomass for the production of electricity has a promising future in California as it is an abundant resource. However the use of biomass is limited, particularly because of the difficulty of collecting and transporting it to power plants and the need for major modification requirements for utilizing solid biomass as feedstock. This two step biomass conversion process could help transform an unrealized potential into practical reality since bio-oil can be easily transported and reformed to produce synthesis gas or hydrogen to offset the use of natural gas in central electric generating plants or distributed power (fuel cell) applications.

Figure 7: Simplified Flow Chart, Wheat Straw to Electricity



2.5.3 Objectives

The goal of this project was to determine the feasibility of producing syngas and/or hydrogen from wheat straw as a feedstock for electric power generation applications by first converting the straw to bio-oil using fast pyrolysis and then reforming the bio-oil to syngas or hydrogen

using a catalytic steam reforming process. The researchers established the following project objectives:

1. Confirm that wheat straw can be pyrolyzed to produce bio-oil fractions. Obtain full closure of mass balance with at least 60 percent yield of bio-oil.
2. Confirm that bio-oil collected from different condensers will have unique physical and chemical properties such as water and lignin content, flash point, density, and viscosity.
3. Construct a reactor system that can be used to reform bio-oil and produce synthesis gas.
4. Demonstrate that bio-oil can be reformed to synthesis gas using a steam reforming technique with a commercial nickel catalyst.
5. Demonstrate that a hydrogen stream of purity no less than 90 percent (dry basis) can be obtained using an advanced steam reformer with a novel core-in-shell catalyst/sorbent material.

2.5.4 Outcomes

The researchers confirmed that wheat straw can be pyrolyzed to produce bio-oil at a reaction temperature of 500°C. They estimated the bio-oil yield to be a total of 50 percent, 35 percent for bio-oil and the remaining 15 percent for char and non-condensable gas byproducts which have some market value. Although the overall yield was less than the target of 60 percent, the researchers believe that the concept has significant upside potential after the system is optimized for performance. Researchers also discovered that wheat straw is more difficult to process than other woods and other fibrous biomass such as corn stover and switch grass. The difficulty was likely caused by the high lignin content along with high inorganic (mineral) matter content of wheat straw materials. In addition, the presence of external inorganic impurities (dirt) may have had an impact on the qualities of bio-oil produced.

The researchers demonstrated that bio-oil produced from wheat straw pyrolysis can be collected into five different fractions using Iowa State University's (ISU) bio-oil fractionating condenser system. Three fractions had water content up to 75 percent and low lignin content of 1 percent to 2 percent. Two fractions had low water content (15 percent) and high lignin content (65 percent). All fractions produced low ash residue of 0.5 percent to 2 percent. Chemical analysis using a gas chromatograph/mass spectrometer (GC/MS) showed that bio-oil fractions with high water content also tend to contain chemical compounds with low molecular weight, such as acetic acid. The fractions with low water content and high lignin content contained high molecular weight components such as anhydrosugars and phenolic compounds. Researchers determined that bio-oil fractions with high water content and low lignin content were the most suitable to be used for catalytic reforming to produce synthesis gas or hydrogen.

The research team successfully constructed a steam reforming reactor system that was able to reform bio-oil to synthesis gas.

The research team demonstrated that bio-oil fractions with high water content and low lignin content can be readily reformed to synthesis gas at 400—600°C using steam reformation in the

presence of a commercial nickel based catalyst. The synthesis gas contained 65 percent hydrogen and 35 percent carbon dioxide. Moreover, catalyst deactivation was not significant. Catalyst deactivation was significant in the case of steam reforming of bio-oil fraction with high lignin content. This behavior was linked to the presence of phenolics that deactivated the catalyst by coking. The researchers concluded that bio-oil fractions with high water content and low lignin content are the most desirable feedstocks for steam reforming of bio-oil to syngas or hydrogen as they have high water, low ash, and low lignin content. They demonstrated that complete steam reforming of all fractions to hydrogen and carbon dioxide was possible without any residual detection of carbon monoxide or hydrocarbons.

The research team achieved synthesis gas with hydrogen purity of at least 98 percent by reforming bio-oil using the novel core-shell catalyst/sorbent steam reformer developed at Iowa State University.

2.5.5 Conclusions

1. The researchers demonstrated that wheat straw can be pyrolyzed to produce bio-oil. It remains to be seen whether a yield of 35 percent low lignin bio-oil plus 15 percent of lesser value byproducts are adequate for this concept to be practical and cost effective.

2. Researchers demonstrated that a fast pyrolysis reactor equipped with a multiple staged condensation unit can produce a variety of bio-oils, each with unique physical and chemical properties. Further optimization could improve the yield of low lignin bio-oil.

3. Researchers found it is feasible to design and construct a steam reformer to reform low lignin bio-oil to syngas.

4. The researchers demonstrated that low lignin bio-oil can be reformed to syngas using a steam reforming reactor with a commercial nickel catalyst. Further work may result in improvements to system efficiency and durability.

5. The research team concluded that the core-shell catalyst/sorbent steam reformer developed at Iowa State University shows promise in obtaining a high level of hydrogen purity from bio-oils without having to worry about poisoning catalysts found in conventional steam reformers. Further study is needed on the bio-oil reforming using the core-shell catalyst/sorbent pellets to determine optimum reaction conditions and results.

6. Researchers were able to demonstrate that wheat straw can be used to produce low lignin bio-oil that can be reformed to either syngas or hydrogen for use in electric generation applications. However it is not clear that this concept is either practical or cost effective compared to other renewable technologies.

2.5.6 Recommendations

The proposed concept has potential but needs additional development work to fully determine system viability and commercial potential. Further research is needed for:

1. Development of new and improved catalysts.

2. Investigation of steam/carbon ratios on product yields.
3. Testing bio-oil reforming at different temperatures and pressures.
4. Optimization of the steam reforming reactor developed at Iowa State University (ISU).
5. Evaluation of gasification techniques to produce synthesis gas as an alternative to catalyst based steam reformation systems.
6. Testing of the system in fluidized bed mode to supplement results achieved from fixed bed mode testing.
7. Determination of the technical and economic feasibility of the proposed process technology at commercial scale.
8. The team should also investigate the feasibility of generating syngas using high temperature electrolysis and gasification techniques.

In addition the research team should conduct a detailed assessment to determine the economic feasibility of this concept compared to other renewable energy alternatives (e.g., solar PV and wind). The feasibility of the concept needs to consider the fact that natural gas prices have stabilized over the past couple of years and may stay relatively low compared to other conventional fuels for the next several years.

The research team needs to conduct a patent search to ensure that this work does not infringe on existing intellectual property.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.5.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

1. Reduced environmental impacts of the California electricity supply, transmission, or distribution system
2. Increased public safety of the California electricity system
3. Increased reliability of the California electricity system
4. Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California electricity supply, transmission, and distribution system. The concept has the potential to reduce the amount of natural gas used in power generation plants which, if successful, could enable a reduction in CO_2 emissions. The CO_2 released from the processing of bio-oil to produce electricity could have a net zero impact on the environment since the straw absorb CO_2 during their growing cycle. It should be noted, however, that there is considerable debate about how much credit biomass products should be given (if any) towards reducing greenhouse gas emissions, particularly if used for the generation of electricity.

Researchers believe that about 50 percent of both wheat and rice straw produced in California could eventually be used for this process for the production of electricity. This equates to 200,000 tons of wheat straw and 150,000 tons of rice straw per year (50 percent of total production in California). Researchers estimate that this could offset the use of natural gas for generating electricity by 2.2×10^6 million Btu per year. The net reduction in CO_2 emissions would be in excess of 115,000 tons/year, assuming that this process has a net zero CO_2 emissions impact to the environment.

2.5.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.5.8.1 Marketing/Connection to the Market

While the connection to the market is clear, the researchers have not reported any connection with companies or organization that could take the technology to market. The researchers' organization, Iowa State University, apparently prefers to license the technology.

2.5.8.2 Engineering/Technical

The research team has a detailed plan outlining the key technical hurdles remaining before this concept can be viable. To execute that plan would, in their estimate, require about two years and up to $1 million.

2.5.8.3 Legal/Contractual

The researchers have not applied for patents. They reported that they have published a technical paper that may have an effect on patent protection.

2.5.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

The technology is still in the early stages of development, so these plans are premature until such time that the concept has been optimized and has a clear path to commercialization.

2.5.8.5 Production Readiness/Commercialization

The concept is not yet sufficiently developed for commercialization. Several technical hurdles need to be addressed and an economic analysis is required to ensure viability of the concept compared to other conventional and emerging technology alternatives.

2.6 Cost Reduction in Solar Cell Electricity by Replacement of Aluminum

Awardee: Priyam, Inc.

Principal Investigator: Saleem H. Zaidi and Sunil Shah

2.6.1 Abstract

A major cost component of crystalline silicon solar cells is the cost of the high quality mono and multi-crystalline silicon wafer starting material. There has been an ongoing effort to reduce wafer thickness to reduce this cost. As wafers have become thinner, however, wafer bowing or warping has emerged as a problem. Bowing arises from thermal expansion mismatch between the silicon wafer and the industry standard screen printed aluminum (Al) backside layer used to create a back surface field (BSF) in the wafer. The BSF significantly reduces free carrier recombination and improves cell performance. Accordingly, there is interest in other methods of creating the BSF to replace the thick Al layer.

The goal of this project was to replace the Al layer by heavily doping the back surface of the wafer with plasma implantation. The researchers proposed using low energy plasma ion immersion implantation of boron (B). The researchers designed, built, and characterized a simple, low cost plasma implantation system using BCl_3 gas as the B source. They then conducted a systematic investigation of plasma process parameters to determine optimum implantation profiles. Process parameters investigated included chamber pressures, implantation times, cathode-anode separation, DC bias, pulse width and repetition rate, and peak plasma current. The researchers characterized the B implantation profiles using four point probe and spreading sheet resistance measurements. They fabricated and characterized boron doped BSF solar cells with diameters up to six inches. These cells were slightly superior to those fabricated with the conventional Al layer BSF process. The researchers inferred typical efficiency to be near 15 percent based on comparison with conventional, textured, SiN passivated simple screen printed solar cells.

Keywords: Silicon solar cells, back surface field, boron doped, plasma ion immersion implantation

2.6.2 Introduction

By Executive Order, California is committed to reducing greenhouse gas emissions and increasing the State's renewable energy portfolio to 33 percent by 2020.[23] Electricity generation by photovoltaic (PV) systems can play an important role in meeting these goals. The demand for PV and its deployment has, however, been held back by high cost. An important factor is the cost of the solar cell modules which constitute 50 to 60 percent of the cost of a PV system.[24] In March 2010 the average retail cost of PV modules of 125 or higher peak watt (Wp) was $4.24/

23 http://gov.ca.gov/press-release/13273/

24 http://www.solarbuzz.com/Moduleprices.htm

Wp, although some retailers sold multi-crystalline silicon modules as low as $1.74/Wp.[2,25] Modules based on crystalline silicon cells are an important component of the PV module market. For example, in 2006 the photovoltaic industry produced 2.54GW of solar cells, 89.9 percent of which were made from mono- or multi-crystalline silicon wafers.[26,27] The current cost of crystalline silicon PV cells is dominated by the cost of the silicon wafer material.[28] To reduce this material cost, there has been a development effort to reduce the thickness of the wafer to get more wafers from a given silicon starting boule. Cell thicknesses in the range of 200 μm or less are now the industrial standard, well beyond the old standard of 330 μm. However, as wafer thickness has been reduced, wafer bowing or warping has emerged as a problem.[29] Bowing in thin wafers arises from thermally induced strain from a thick screen printed and fired Al paste commonly used for the formation of a back surface field (BSF) in the wafer. The paste firing is done in a rapid thermal annealing (RTA) furnace and must be carefully controlled to achieve a reduced carrier recombination at the back surface.[30,31] For these reasons, a need exists for an alternative to the thick screen printed and fired Al paste method of forming a back surface field.

If the wafer bowing problem could be solved, there could be significant cost reduction due to less consumption of silicon per watt produced. The researchers estimated that the silicon content (2006) is roughly 13 g/W_P for mono and multi-crystalline Si solar cells and about 7 to 8g/W_P for edge defined film fed growth (EFG) and string ribbon solar cells (STR). Improved processes could reduce the silicon content to figures in the order of 9g/Wp for mono and multi-

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25 Also see http://sunelec.com/

26 Neuhaus, D.H. and A. Munzer, "Industrial Silicon Wafer Solar Cells," *Advances in OptoElectronics*, Volume 2007, Article ID 24521.

27 Münzer, K.A., R.R. King, R.E. Schlosser, J. Schmalzbauer, S. Sterk, and H.L.Mayr, "Manufacturing of back surface field for industrial application," in *Proceedings of the 13th European Photovoltaic Solar Energy Conference (EU PVSEC '95)*, Nice, France, October 1995. p. 1398.

28 Glunz, S, "High-Efficiency Crystalline Silicon Solar Cells," *Advances in OptoElectronics*, Volume 2007, Article ID 97370, http://downloads.hindawi.com/journals/aoe/2007/097370.pdf

29 http://www.ipcrystalclear.info/data/pdf/SP4 percent20paper percent20for percent20EUPVSEC21 percent20(IMEC, percent20Agostinelli percent20et percent20al)- percent20Cells percent20on percent20ultra-thin percent20substrates.pdf

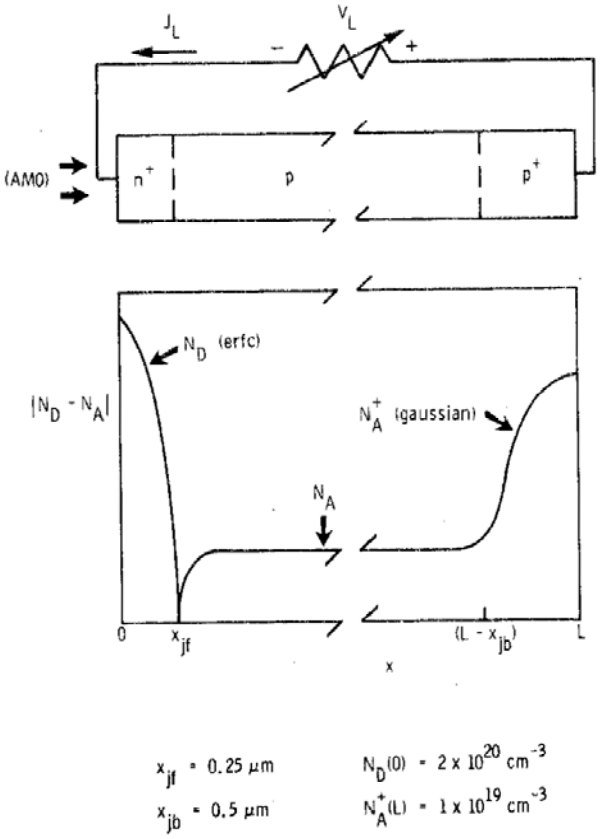
30 Fossum, J.G., R.D. Nasby, and S.C. Pao, "Physics underlying the performance of back-surface-field solar cells," *IEEE Transactions on Electron Devices*. Vol. ED-27, April 1980, pp. 785-791.

31 Narasimha, S, A. Rohatgi, and A.W. Weeber, "An Optimized Rapid Aluminum Back Surface Field Technique for Silicon Solar Cells," *IEEE Transactions on Electron Devices*, Vol. 46, July 1999, pp. 1363-1370.

crystalline and would reduce it to about $3g/W_P$ for ribbons. First calculations indicate this reduction in silicon content could reduce cell cost by 20 percent and 30 percent, respectively, which translates into 15 percent and 20 percent cost savings at module level. The cost reduction at system level, which ultimately determines the price per kWh of PV electricity, would be 9 to 12 percent. Energy payback time would lower to 1.5 to 3 years for crystalline modules and 1 to 1.5 years for ribbons.

The advancement of science proposed in this project was to replace the Al paste screen printed and fired back surface field p+ layer (Al^{3+}). This p+ layer is shown schematically in Figure 8. The requirement of firing the Al paste with a carefully controlled RTA thermal treatment would be eliminated. Instead, the researchers proposed a boron doped p+ layer (B^{3+}) formed by plasma ion implantation of B. The plasma implanted doping would be carried out with BF_3 gas in a modified commercially available sputter coating system. A second step would be to give the implanted layer activation anneal in a standard laboratory conveyor belt furnace. Thermal control requirements in the belt furnace process would be less stringent than in the Al layer firing. In other respects the cell would be processed using standard techniques for front surface contacts, surface passivation, and anti-reflection coatings.

Figure 8: The P^+ Layer



The back surface field in the p+ region on the right suppresses free carrier recombination at the back surface by repelling photo-generated minority carriers in the p-type base region which diffuse to the back surface.[32]

2.6.3 Objectives

The goal of this project was to determine the feasibility of using plasma immersion ion implantation technology to replace Al back surface field by boron doped local back surface field in solar cell manufacturing to reduce costs and enhance performance. The researchers established the following project objectives:

1. Finalize system design. Complete drawings and identify parts.
2. Modify working Innotec sputtering chamber for plasma immersion ion implantation (PIII). Demonstrate that the system displays all operating processing conditions such as BF_3 pressure, gas flow, voltage, vacuum, etc. Demonstrate plasma discharge.
3. Implant 150 mm diameter test wafers at several doses and pressures. Evaluate implant annealing parameters with LTA-306. Measure carrier lifetime, sheet resistance, and reflectance. Optimize implant RTA annealing processes to match Al back surface field (BSF) resistance profile.
4. Implant device wafers. Use optimized operating conditions from Objective 3.
5. Conduct prototype parametric and reliability testing. Demonstrate efficiency comparable to standard Al paste process. Demonstrate comparable electrical test parameters. Demonstrate that device can operate at least 500 hours without failure under UV, humidity, and temperature stress.
6. Perform manufacturing cost analysis. Verify that projected manufacturing cost of PIII is 25 percent lower than Al BSF on cost per watt basis.

2.6.4 Outcomes

1. The researchers completed the implanter system design.
2. The researchers modified the sputtering chamber to have parallel plate geometry with variable spacing and variable DC bias. Mass flow controllers controlled BF_3 dopant concentration and chamber pressure. A visible plasma discharge was demonstrated.
3. Researchers implanted test wafers of 100 mm and 150 mm with three configurations of power supplies. They measured boron dose, depth, and sheet resistance. They evaluated annealing protocols in a six zone furnace. Importantly, however, they did not measure carrier lifetime and reflectance.
4. Researchers implanted a number of 150 mm wafers with B on the back surface and fabricated into solar cells. The B source was BCl_3 rather than BF_3. The researchers B

32 Fossum, J.G., "Physical Operation of Back-Surface-Field Silicon Solar Cells," *IEEE Transactions on Electron Devices*, Vol. ED-24, No. 4, April 1977, pp. 322-325.

doped the starting wafers [100] of thickness 550 μm with resistivity ~1-10 ohm-cm. They used standard industrial steps of front surface texturing, doping, passivation, and screen printed contacts fired to create solar cells. They carried out activation of the B implanted layer in a six zone belt furnace. The researchers fabricated control solar cells using the standard screen printed Al BSF layer for comparison measurements. Except for B implantation and its back surface contact pattern, all processing steps were identical.

5. The researchers measured the B doped BSF cells with a Xe arc pulsed source and compared them with the performance of their standard Al paste BSF samples. They estimated efficiency of about 15 percent by comparison with a standard Al paste BSF sample. They did not present measured efficiency data. The researchers stated the implanted samples had comparable or slightly higher efficiency and similar electrical parameters. They did not do UV, humidity, and stress testing and did not measure lifetime. Lamination tests on B implanted and Al paste BSF showed no difference in behavior, indicating environmental protection by lamination may be adequate.

6. The researchers performed a manufacturing cost analysis as a function of assumed efficiency. They found that for an assumed efficiency of 15 percent, the B implanted BSF cell had a cost advantage over the Al paste BSF of $345800/10MW or about $0.035/W. Apparently they included only material costs for Al and BCl_3 and not equipment and operating costs in this analysis.

2.6.5 Conclusions

1. The researchers successfully completed the implanter system design.

2. The researchers successfully modified the sputtering chamber for ion implantation.

3. The researchers found a useful plasma power delivery mode. They did not measure values for carrier lifetime and reflectance, which would be important pieces of information in assessing device performance and future development directions. Carrier lifetime and inferred surface recombination data are important for success in the goal of thinner wafers.

4. The researchers demonstrated compatibility of implanted B back surface with standard industrial process steps of front surface texturing, doping, passivation, and fired screen printed contacts.

5. The researchers inferred the efficiency of the 550 μm thick B doped BSF cells was about 15 percent. Industry standard tests should be accomplished to confirm the efficiency.

6. The researchers did not perform a complete cost analysis. They did not include equipment costs and operating costs.

The goal of this project was to determine the feasibility of using plasma immersion ion implantation technology to replace Al back surface field by boron doped local back surface field. The project gave indications of feasibility for the replacement of Al and the potential for

cost reduction. Enhanced performance still must be demonstrated by measurement on thinner cells.

2.6.6 Recommendations

The Program Administrator (PA) recommends that the researchers measure the recombination time as a function of wafer thickness to assess the back surface recombination velocity. The PA also recommends a demonstration of unbowed cell fabrication on much thinner cells, followed by a direct measure of the efficiency of those cells. This will prove ultimate practical feasibility of the approach.

The researchers should carry out a more complete cost analysis on thin B implanted BSF cells compared to thick Al paste BSF which includes equipment costs and operating costs.

The PA also recommends that the researchers carry out a direct measurement of cell efficiency and free carrier recombination time and demonstrate their BSF technique on thinner wafers.

2.6.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

1. Reduced environmental impacts of the California electricity supply, transmission, or distribution system
2. Increased public safety of the California electricity system
3. Increased reliability of the California electricity system
4. Increased affordability of electricity in California

The primary benefit to the ratepayer from this research would be reduced environmental impacts of the California electricity supply, transmission, and distribution system by replacing carbon based fuels for power generation. If the wafer bowing problem is solved, there could be significant cost reduction in silicon based PV systems and a concomitant displacement of fueled generation systems. Improved processes could reduce the silicon content to 9g/Wp for mono and multi-crystalline and about 3g/Wp for ribbons. First calculations indicate that this could reduce cell cost by 20 percent and 30 percent, respectively, which translates to 15 percent and 20 percent cost savings at module level. The cost reduction at system level, which ultimately determines the price per kWh of PV electricity, could be 9 to 12 percent. Energy payback time could be lowered to 1.5 to 3 years for crystalline modules and 1 to 1.5 years for ribbons.

2.6.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.6.8.1 Marketing/Connection to the Market

The researchers published two papers on their work without compromising the potential to secure patent coverage. They were working with a major semiconductor manufacturer to secure

a partnership agreement to bring their technology to market. The researchers were seeking help in forming a partnership agreement.

2.6.8.2 Engineering/Technical

The researchers developed an engineering requirements specification and stated that they could complete the engineering development in two years using internal financial resources.

2.6.8.3 Legal/Contractual

The researchers had not applied for nor were granted any patents by the end of this project.

2.6.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

At this stage of development it appears premature to engage in additional testing for environmental, safety, risk assessments/quality plans.

2.6.8.5 Production Readiness/Commercialization

Until the researchers prove feasibility of their process and clearly demonstrate the performance of the resulting cells, there is no need to discuss production readiness. The researchers completed a commercialization plan after the completion of this project

2.7 Innovative Design of High Solids Digestion Plants for Economic and Renewable Energy Production

Awardee: Washington State University

Principal Investigator: Shulin Chen

2.7.1 Abstract

This research project developed a new type of a high solids anaerobic digestion (HSAD) system with the goal of producing more biogas at lower costs than existing technologies. The innovation offered in this HSAD system was growing of anaerobic bacteria in a separate high rate seed digester using leachate from the organic fraction of solid wastes. This new seed digester was an expanded bed type reactor, also known as the upward flow anaerobic sludge blanket (UASB) reactor, presently used in industry for treating liquid organic waste streams with solids contents in the 1 to 3 percent range.[33] By laterally mixing the solids reactor and continuously percolating the bacterial seed into the solids reactor, the researchers achieved improved solid waste degradation and subsequent higher methane production, while avoiding solids recycling. They maintained the new HSAD system consisting of a bench scale seed reactor and a bench scale solids reactor at the mesophilic temperature of 35° C. The researchers evaluated and validated the process with the help of advanced modeling techniques based on the International Water Association (IWA) Anaerobic Digestion Model No. 1(ADM1).[34] When the researchers treated solid food wastes (defined by total solids content of 15 percent or higher) in the HSAD system, they achieved higher loading rates of .06 metric tons of solid waste/m^3/day

33 http://www.usab.org/discover/agsb.htm#egsb

34 http://www.enviornmental-xpert.com/resultEachPublication.aspx?cid=5302&codi=1525&iproducttype=5

compared with .04 metric tons of solid waste/m^3/day for existing food waste digesters. The corresponding organic loading rate of the new HSAD system was 78 kg-COD/ m^3/day. The researchers achieved specific biogas production rates of 4.62 m^3/m^3/day compared with 2.8 m^3/m^3/day production from existing food wastes digestion systems. The methane content of the biogas was in the range of 50 to 70 percent by volume. The savings in capital and operation costs of the new HSAD system were 31 percent compared with conventional HSAD technology with solids recycle. The overall savings in biogas and energy production from the new HSAD system could be as much as $2.5 billion if all organic wastes in California were treated by this system.

Keywords: Food wastes, organic solid wastes, high solids anaerobic digestion, methane, biogas

2.7.2 Introduction

The California energy problem this project addresses is the potential conversion of higher solids content organic wastes to methane via anaerobic digestion by a new process that may lower the costs and increase the efficiency of biogas production. Presently there are a total of 82 million dry tons per year of biomass and organic wastes produced in California, along with 11 million dry tons of municipal solid wastes (MSW). Instead of depositing these wastes in landfills where environmental damage from emissions into air and water may occur, the organic fraction of these wastes could be treated in a completely enclosed system.

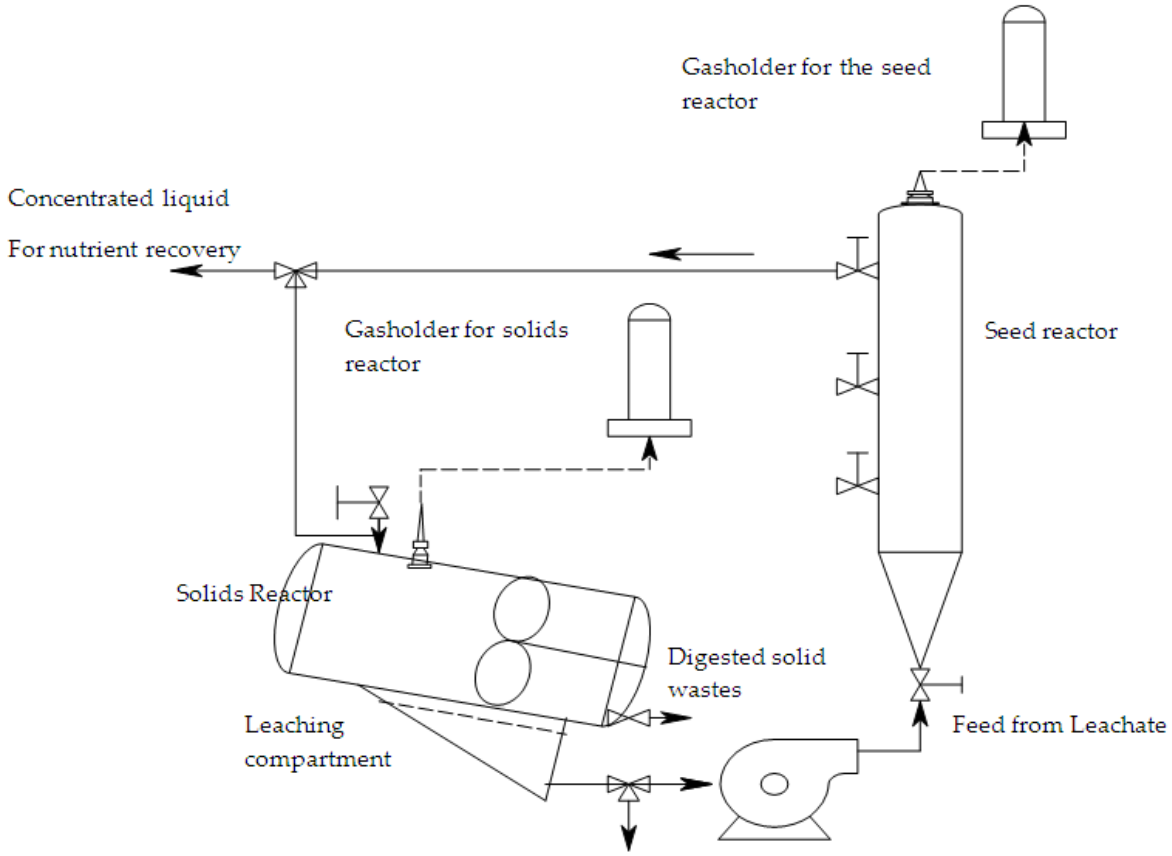
The major benefit to California ratepayers if such a system were economically viable is the energy production possible from the conversion of these wastes via the biological process of anaerobic digestion. The researchers performed an extensive study of the organic wastes that would be available for digestion, and this study was included in Appendix I of their final report. If the organic food wastes portion of MSW, livestock and poultry manure, and biosolids from sewage treatment plants were digested and the resulting methane converted into electricity, annual energy production would be 5.130 GWh. Dairy manure and food wastes would constitute 1.262 GWh and 1.229 GWh, respectively. Based on the savings per kWh that were claimed by the researchers for their HSAD process compared with existing high solids digestion systems, total California savings would be $2.5 billion. While the savings number is impressive, the projected cost of electricity produced by either the proposed system or the conventional system is quite high. The researchers calculated the cost of electricity using the new HSAD system with augmentation at $1.07 per kWh compared to the cost using the conventional process at $1.55 per kWh. While both numbers are quite high, this project made a significant reduction in the cost of converting food wastes to electricity.

The advancement of technology proposed was a variation of a high solids digestion system where the high solids digester is augmented by a liquid seed digester that circulates its contents through the solids digester, thus enhancing the reactions in the overall system. The new process has a significant advantage in that it can be applied to high solids waste streams of more than 20 percent total solids (TS). Existing high solids digestion technologies that are mainly applied in Europe to MSW treatment depend on recycling significant amounts of the treated solids to maintain the bacterial population in the digester. The biological reaction, however, is limited by

the bacterial population in an anaerobic digester. The recycling of treated solids requires additional reactor volumes and expensive equipment.

The process tested in this project relies on growing the bacteria separately at a high rate (augmentation) to continuously seed the process, lower its inhibition, and enhance the hydrolysis of particulate organic fractions. Therefore the efficiency of the whole treatment system could be increased and the cost of the system decreased. The tested process integrated two unit processes. The first process was the mechanically mixed solids reactor treating influent at 15 to 20 percent TS. The leachate from that process was fed to the second process that operated in an up flow expanded sludge bed mode. The bacterial population was enriched in the second reactor (seed reactor) and the washed out portion was recycled to seed the solids reactor and to enhance the leaching process. The process schematic is shown in Figure 9 and a photo of the actual experimental setup is shown in Figure 10.

Figure 9: Schematic of the New HSAD System



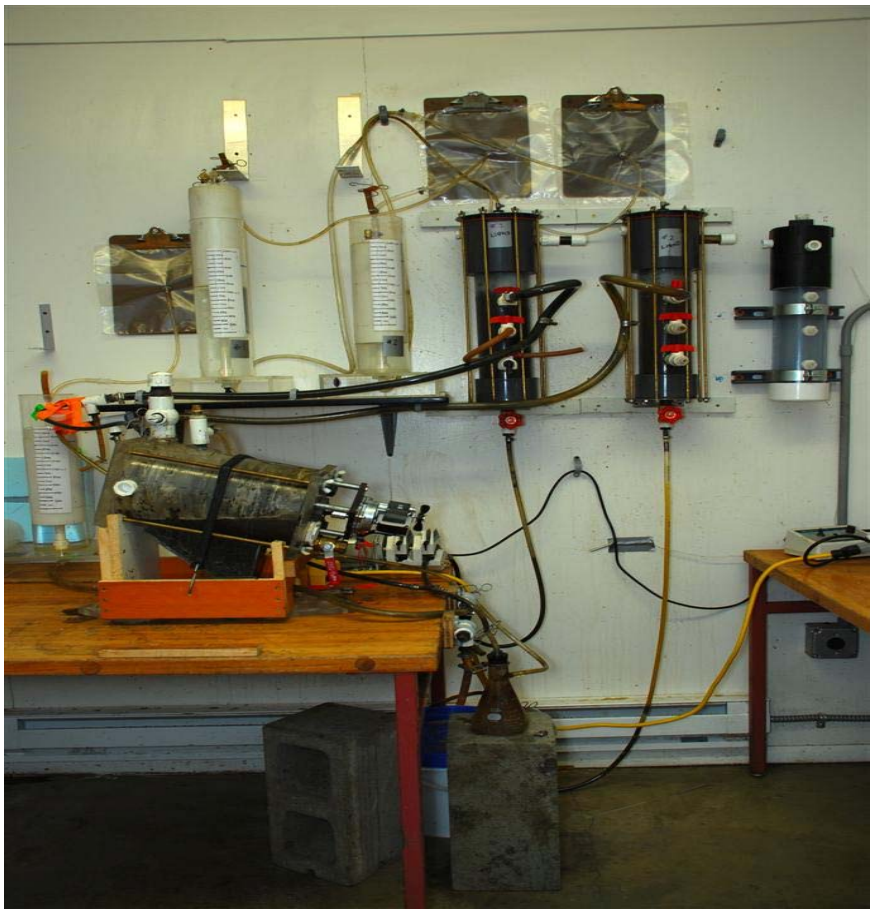
2.7.3 Objectives

The goal of this project was to determine the feasibility of a high solids anaerobic digestion system (HSAD) to lower the cost while increasing the gas production compared with existing commercial high solids digestion systems. This new process utilized a liquid seed digester that circulated digestate with a high methanogenic bacterial level into the solids digester where the anaerobic reactions were enhanced while lowering the operating costs of mixing. The researchers established the following project objectives:

Determine the target biomass feedstocks in California that are best suited to anaerobic digestion based on their annual production quantities of over 1000 tons/year, organic content at least 80 percent, and potential biogas production of greater than one cubic foot per pound of wet as-produced biomass.

Develop a liquid seed digestion system that, using the leachate from the solids digester as influent, produces effluent with volatile solids contents of 10,000 mg per liter for providing bacterial enrichment for the solids digester.

Figure 10: Photo of Experimental HSAD System



Test the experimental setup integrating the solids reactor with seed reactor to demonstrate the process improvement due to augmentation and continuous seeding. The quantitative proof of improvement is to be: reactor effective volume equal to 90 percent of the geometric volume, and biogas production equal to 90 percent of the theoretical biogas production of the organic fraction of the treated waste.

Develop mathematical models for the process, including: an anaerobic digestion process model calibrated for the selected feedstock, and a complete and validated simulation tool of the new process system of reactors.

Evaluate the economics of the new HSAD system and show improvement of the new system economic value compared with existing systems as follows: 20 percent savings due to improved biogas production per unit volume of reactor, and 30 percent cost reduction due to savings in solids recycling.

2.7.4 Outcomes

Dairy manure and food wastes provide the largest quantities of organic wastes produced year round in California: 3,857,800 dry tons and 1,920,700 dry tons, respectively. The researchers determined the organic content of these materials to be 91 percent for dairy manure and 89 percent for food wastes dry matter. The potential biogas production from dairy manure and food wastes is 834 and 847 cubic meters per ton dry matter, respectively. Based on the dry matter content (14 percent) of these materials as produced, this is the equivalent of approximately 1.9 cubic feet of biogas per pound of as produced waste. The estimated potential electrical power generation from methane produced from the anaerobic digestion of municipal solid wastes food fraction and dairy manure in California was 1,229 GWh and 1,262 GWh, respectively. The researchers estimated total electrical energy at 5,130 GWh if all digestible waste were converted using this process.

The researchers used two lab scale-up flow reactors to grow the bacterial seed on the extracted liquid from dairy manure and food wastes. They seeded these reactors with anaerobic sludge and ran them at 35° C. Using the seed reactor with screened manure produced 2 percent VS, exceeding the target of 10,000 mg/l or 1 percent VS. However, the seed reactor for food wastes achieved outputs of only 0 .7 percent VS, under the targeted volatile solids content.

The researchers initialized the solids reactors with the anaerobic sludge inoculum from the previous seed reactor experiment. They found the dairy manure digester could not be operated in concert with the seed reactor because of the fiber content of the manure. The solid food wastes reactor feed contained 15 percent TS and could operate in concert with the seed reactor. Researchers maintained the solids volume at three liters and the liquid volume in the seed reactor at two liters. They maintained the intermittent recycle rate of leachate through the seed reactor at 250 mL/h for two hours each day. The steady state results of biogas production rate from the solids reactor from day 25 to day 45 were used to estimate its effective volume. The estimated solids reactor effective volume was 2.9 L. Compared with the geometric three liter experimental volume, the solids reactor effective volume was 97 percent, which was greater than the target of 90 percent. The researchers reported the methane productivity of the

optimized HSAD system to be 2.28 m^3/ m^3/day, which corresponded to a methane efficiency of 96 percent compared to the target methane production. However, the final report did not clearly explain the connection between the actual methane production from the experimental reactors, listed at between two and six liters per day, and the claimed methane productivities stated above.

The researchers developed and validated a set of mathematical models for the seed reactor and the integrated setup experiments. They found the validated models were useful in optimizing the new system, setting the design criteria for scaling the process, and evaluating the new system economics.

The new HSAD system reduced the solids reactor volume, eliminated solids recycle, and reduced solids mixing due to process augmentation. Based on preliminary estimation, the biogas production per unit volume of the solids reactor contributed savings of 32 percent on capital compared with a conventional HSAD system with solid recycling. The researchers eliminated solids recycle from the new system, reducing operation costs by 33 percent.

2.7.5 Conclusions

The inventory of biomass sources in California revealed the two highest volumes of wastes, dairy manure and organic fraction of municipal solid wastes (primarily food), could be digested to produce methane that, when converted to electricity, could produce as much as 1262 Gwh (dairy manure) and 1229 Gwh (food wastes) annually.

The researchers successfully maintained the seed reactor for the dairy wastes leachate at 2 percent TS, double the goal of 1 percent TS. However, the food wastes seed reactor could only be maintained at 0.7 percent TS, under the target of 1 percent TS.

The researchers validated mathematical models of digestion using the data from the experimental digesters operated during this project.

The researchers demonstrated:

1. 50 percent higher organic loading rates per volume of digester.
2. 50 percent higher biogas production rates per volume of digester with the new HSAD system.
3. The economic savings as a result of the higher efficiency of the new HSAD system was approximately 30 percent compared with conventional high solids digestion systems.
4. While the researchers made significant progress in reducing the cost of electricity produced from food wastes, the net cost to the consumer was still quite high, even when compared with solar photovoltaic electricity.
5. Overall the researchers proved the feasibility of the proposed process when applied to organic food wastes.

2.7.6 Recommendations

The Program Administrator recommends placing emphasis in the area of solids mixing since this one sub-process accounts for 75 percent of the operational costs. In addition, computational dynamic modeling of the following parameters should be performed:

1. Mixing of the solids reactor
2. Seed recycle rate
3. Up-flow velocity in the seed reactor to maintain the suspension of the sludge bed along the seed reactor
4. Settings of the reactor heating systems

A small demonstration plant treating 10 kg per day of solid food wastes could be suitable to optimize these parameters. This would require a small scale solids reactor and seed reactor of 200 liter volume. Ultimately, an automated small scale plant could be used to demonstrate the new system and optimize its settings for different feedstock and field applications.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.7.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

Reduced environmental impacts of the California electricity supply, transmission, or distribution system

1. Increased public safety of the California electricity system
2. Increased reliability of the California electricity system
3. Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is from reduced environmental impacts of the California electricity supply or distribution systems. This benefit would be achieved by providing a more cost effective method of digestion of high solids organic wastes, in particular the food portion of municipal solid wastes. The researchers demonstrated that up to 1229 GWh of electrical energy could be produced from the digestion of food wastes. If valued at $0.10 per kWh, this energy would be worth $123 million annually. However, using the developed process the current cost of production is well above $0.10 per kWh. Other benefits accrue from the developed process. Nutrients concentrated in a waste stream could be recovered and used as

fertilizer. The production potential is 2.1 kg of nitrogen per ton of treated waste and 3.7 kg of potassium per ton of treated waste. Recovery and reuse of these nutrients would reduce a waste disposal problem.

2.7.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.7.8.1 Marketing/Connection to the Market

The researchers had not talked with potential customers by the end of the project. To bring the results of this project to market they will require a partnership of some form with a commercial business.

2.7.8.2 Engineering/Technical

The researchers identified a technical development path. They indicated a need for additional funding and approximately two years to complete the development tasks.

2.7.8.3 Legal/Contractual

The researchers performed a rudimentary patent search and found no potential infringements. They had not applied for patents at the end of the project.

2.7.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

While no problems were identified, these plans need to be evaluated in detail prior to commercialization.

2.7.8.5 Production Readiness/Commercialization

The researchers had not produced a production readiness plan by the end of the project. They need to design, build, and test a larger prototype before they can address this issue. However, it is not too early to engage a commercial partner.

2.8 Hybrid DC and AC Linked Micro-Grids

Awardee: University of Miami

Principal Investigator: Zhenhua Jiang

2.8.1 Abstract

Distributed generation systems on the customer side of the meter remain a preferred energy solution to several issues facing California. However utility electric power distribution systems were not designed to accommodate power generation on the customer side. Isolating some portions of the grid as self-regulating micro-grids has been proposed as one promising approach. The goal of this project was to determine the feasibility of a hybrid direct current (DC) and alternating current (AC) linked micro-grid strategy that aimed to increase the control flexibility. Towards this end, this project developed a hierarchical structure for the micro-grid with both DC and AC links, identified behavioral functions and control objectives of each level,

developed strategies for various controllers, evaluated the system performance, and assessed the system reliability.

Through this project, researchers demonstrated that in a hybrid DC and AC linked micro-grid the DC and AC zones may be controlled separately. The number of inverters needed for certain DC generators may be reduced, and the variations of DC bus voltages can be maintained within 10 percent with appropriate controls. The micro-grid can sustain certain amounts of fault currents when integrated with a utility grid at a 12 kV level with a typical capacity of 10 MW. The hybrid DC and AC linked micro-grid paradigm provides a flexible control system for integrating a set of distributed energy resources into utility grids, enables a plug-and-play capability, and could facilitate the safe utilization of a variety of distributed energy resources. For a commercial proof of concept of this technology, however, a test of the hybrid micro-grid connected to a conventional electric distribution system serving in parallel to a secondary electric distribution system is required.

Keywords: Energy system integration, distributed energy resources, micro-grid, fuel cells, renewable energy, energy storage, power distribution systems, grid integration, interfaces, power electronics

2.8.2 Introduction

The expanded use of distributed energy resources in California, including small energy generators on the customer side of the meter, is a policy preference.[35] The ability to interconnect renewable and other distributed sources with low environmental impact is attractive and is gaining increased attention. Furthermore, distributed energy resources can benefit the electric utilities by reducing congestion on the grid, reducing the need for additional generation and transmission capacity, and offering ancillary services such as local voltage support. However the traditional utility electric power distribution systems cannot readily accommodate significant levels of active generation on the customer side. The technical issues involved in effectively integrating these distributed resources with grid operations are significant and critical; they must be appropriately addressed before actual benefits can be achieved.

Previous efforts have focused on interconnecting a relatively limited number of small sources to the power transmission network and studying their impacts on the grid performance.[36] Recent

35 California Energy Commission 2008, *2008 Integrated Energy Policy Report Update*, CEC-100-2008-008-CMF, p.18.

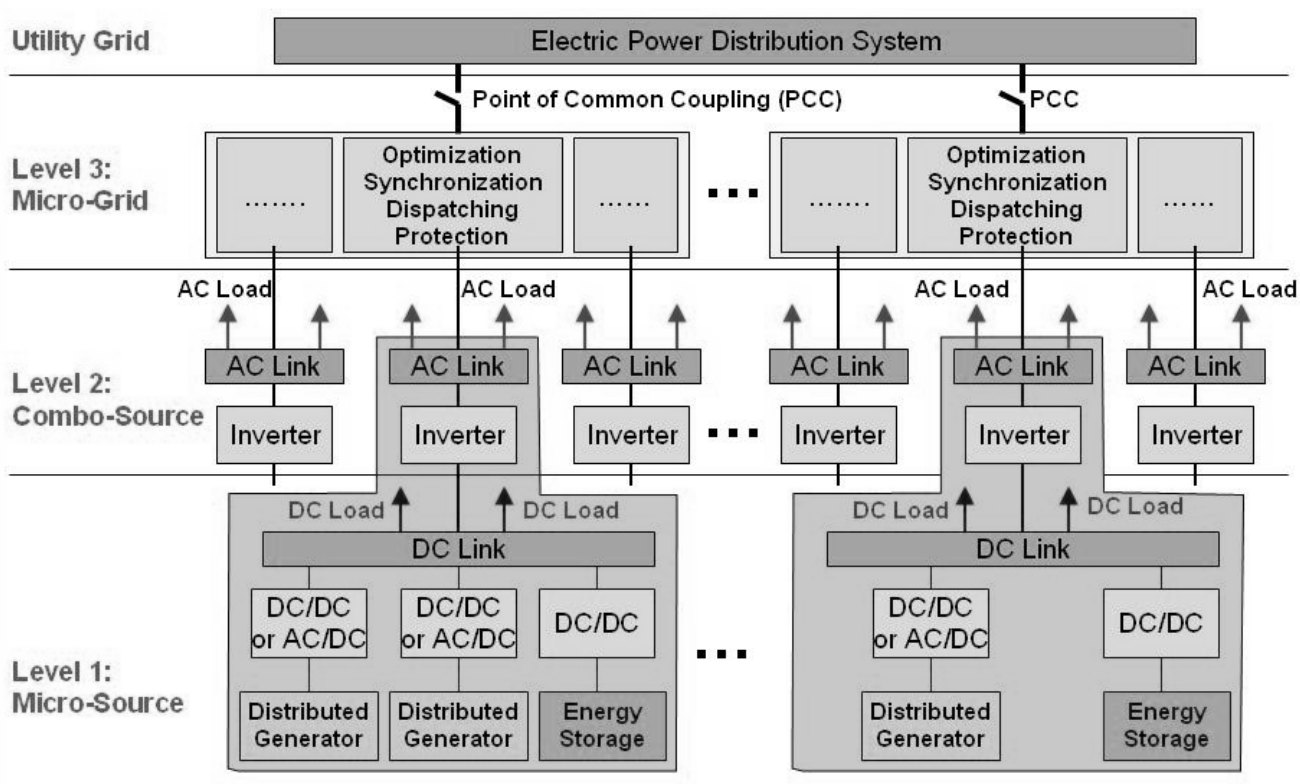
36 T. S. Basso, and R. DeBlasio, "IEEE 1547 series of standards: interconnection issues", *IEEE Transactions on Power Electronics*, Vol. 19, No. 5, pp. 1159 – 1162, Sept. 2004, and F. Pilo, G. Celli, and S. Mocci, "Improvement of reliability in active networks with intentional islanding", *Proceedings of the 2004 IEEE International Conference on Electric Utility Deregulation, Restructuring and Power Technologies*, Vol. 2, pp. 474 – 479, April 2004.

work concentrated on a solution of integrating a cluster of distributed energy resources and loads into micro-grids and interconnecting those with power distribution networks.[37]

As an essential step to realize the micro-grid concept, this project sought an innovative approach to integrating a set of distributed energy resources into the bulk electric grid through micro-grids with both DC and AC links. The goal of this project was to determine the feasibility of the hybrid DC and AC linked micro-grid paradigm that aims to increase control flexibility. The specific need that was investigated in this project related to novel approaches that enable safe, reliable, and cost effective integration of distributed energy resources into the distribution system. Figure 11 illustrates the major components of a hierarchical micro-grid with both DC and AC links.

The proposed project included computer simulation only, with no laboratory or field work.

Figure 11: Illustration of a Hierarchical Micro-Grid with Both DC and AC Links



37 R. Lasseter, A. Akhi1.C. Mamay, J. Stephens, J. Dagle, R. Gullromson, A. Meliopoulos, R. Yinger and J. Eto, "White Paper on integration of distributed energy resources - The CERTS MicroGrid concept." LBNL-50829, Office of Power Technologies, the US Department of Energy, Contract DE-AC03-76SFW098, April 2002.

2.8.3 Objectives

The goal of this project was to develop effective strategies for simultaneous control of DC, AC, and synchronous links in the micro-grid to ensure robust grid control. The researchers established the following project objectives:

1. Achieve an abstract (system level) framework for the hybrid DC and AC linked micro-grid.
2. Achieve a detailed framework for the hybrid DC and AC linked micro-grid.
3. Obtain control strategies for DC, AC, and synchronous links within a micro-grid and computer models for these control algorithms.
4. Demonstrate that a hybrid DC and AC coupled micro-grid is robust, the control strategies work well with the hybrid micro-grid, the number of inverters can be reduced by 50 percent, and the variations of DC bus voltages can be maintained within 10 percent through appropriate controls.
5. Confirm from the project findings that the micro-grid can sustain certain amounts of fault currents when integrated with a utility grid at a 12 kV level with a typical capacity of 10 MW.

2.8.4 Outcomes

1. The researchers developed a conceptual model of the hybrid DC and AC linked micro-grid, focused on a three level, hierarchical structure with DC, AC, and synchronous links.
2. The researchers developed a detailed framework for the hybrid DC and AC linked micro-grid, including behavioral functions and control objectives of each level in the hierarchical structure.
3. The researchers developed control strategies for simultaneous control of DC, AC, and synchronous links.
4. The researchers completed computer simulation models to study the steady state and dynamic performances of hybrid DC and AC linked micro-grids using a virtual test bed (VTB) environment. Simulation results demonstrated that a hybrid micro-grid with both DC and AC links can be robust, that the control strategies developed for both DC and AC zones worked with the hybrid micro-grid, and that the variations of DC bus voltages could be maintained within 10 percent through proper controls.
5. The researchers demonstrated, using the VTB, that a hybrid micro-grid could sustain certain amounts of fault currents when integrated with a utility grid at a 12 kV level with a typical capacity of 10 MW. The researchers confirmed that the hybrid DC and AC linked micro-grid was able to sustain a fault current of 100 ampere without disconnecting distributed generators and sustain a fault current of 200 ampere with a 10 percent voltage drop.

2.8.5 Conclusions

Research results suggest that, in a hybrid micro-grid, the DC and AC zones can be decoupled and then controlled separately and effectively. The DC portion of the micro-grid can regulate the output power from each source and support the DC bus voltage. The AC portion of the micro-grid can be controlled separately to regulate the active and reactive power from each generation and/or storage source and support the AC bus voltage and frequency. In the grid-connected mode, the active and reactive power can be independently controlled. In the isolated mode, the output voltage as well as active and reactive power can be appropriately controlled. The hybrid DC and AC linked micro-grid paradigm provides a flexible, reliable solution to the integration of distributed energy resources into utility grids. The micro-grid may enable a plug-and-play capability, and it could facilitate the safe utilization of a variety of distributed energy resources. This research project verified the feasibility of the hybrid DC and AC linked micro-grid hierarchy concept. It is important to recognize and account for the fact that there may be separate and diverse control schemes and hierarchy approaches for varying bundles of distributed resources in independent micro-grids and that compatibility between various approaches also needs to be considered.

2.8.6 Recommendations

The Program Administrator recommends:

1. Test the hierarchy control scheme in a real world grid connected (secondary distribution level) test.
2. Develop protocol standards for compliance with IEEE standard 1547 and begin safety standards development.
3. Evaluate compatibility issues with interconnected micro-grids using different control and structure concepts.
4. Evaluate and document costs to implement and compare this scheme's benefits with other micro-grid approaches.
5. Determine and document boundary and size limit conditions for each layer of the hierarchy and effects on control topology for different sizes.
6. Investigate how the hierarchy can allow for the growth in different layers and accommodate manual or automatic regrouping of generation components within or across hierarchy levels or accommodate multiple levels.
7. Investigate adaptive learning to allow for smart micro-grid control and management.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.8.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

1. Reduced environmental impacts of the California electricity supply, transmission, or distribution system
2. Increased public safety of the California electricity system
3. Increased reliability of the California electricity system
4. Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is from reduced environmental impacts of the California electricity supply system. Distributed generation promises significant reductions in the environmental impacts of the California electricity supply and transmission and distribution system. This technology concept may increase the use of distributed generation by allowing improved integration with the bulk power delivery system.

2.8.8 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.8.8.1 Marketing/Connection to the Market

The researchers were in discussions with the University of Miami to install and test such a system. Publication of those results, if completed, would be crucial to advancing the concept. The researchers discussed the concept with Pareto Energy Company, which has an interest in developing a commercial micro-grid.

2.8.8.2 Engineering/Technical

The researchers received additional funding from the National Science Foundation to develop and evaluate a laboratory scale micro-grid consisting of a large set of distributed energy resources.

2.8.8.3 Legal/Contractual

The researchers had not applied for any patents as a result of this research nor entered into any formal agreements with potential developers of the technology concept.

2.8.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

The researchers must ensure and document that the concept complies with IEEE Standard 1547 and related standards dealing with worker safety (e.g., disconnect) for interconnection of distributed generation systems.

2.8.8.5 Production Readiness/Commercialization

The concept is not ready for commercialization until a real world test has been completed and interconnection issues are resolved.

2.9 Determining the Feasibility of a High Temperature CO2 Separation Membrane

Awardee: Columbia University

Principal Investigator: Klaus S. Lackner

2.9.1 Abstract

Managing CO_2 gas emissions from the combustion of carbon based fuels is proving to be a difficult challenge. Capturing carbon dioxide requires novel techniques that have low energy and economic penalties. High temperature membrane separation of carbon dioxide from exhaust gasses could be useful in advancing carbon management technologies.

This project examined the feasibility of a dense dual-ion conducting membrane that can selectively separate CO_2 from flue gas at temperatures greater than 400° C. The basic idea was to combine oxygen ion conductivity of a solid oxide electrolyte with the carbonate ion conductivity of a molten carbonate electrolyte into a composite membrane. In this composite membrane a CO_2 trans-membrane pressure difference drives a current of carbonate ions moving one way through a molten carbonate. Oxygen ions return through the solid oxide phase, the net result being the neutral transport of CO_2 across the membrane. Such a membrane has the potential to provide a mechanically simple low cost and low parasitic energy method to separate CO_2 from process gasses at high temperatures.

The researchers demonstrated proof of concept of high temperature selective removal of CO_2 using membranes. Membranes constructed of alkali metal carbonates and gadolinia-doped ceria appeared most promising based on in-cell degradation reactions, lifetime, and permeability compared to the other membrane materials evaluated.

Keywords: CO_2, carbon capture, gas separation membrane, high temperature, dual phase membrane

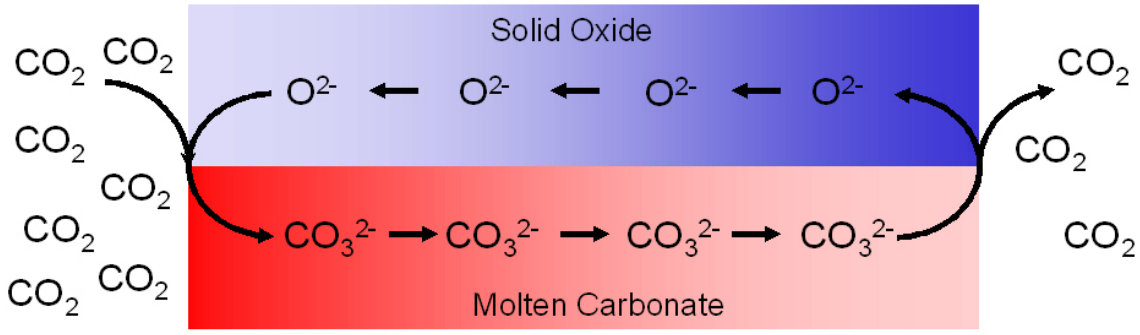
2.9.2 Introduction

Carbon capture and storage (CCS) from point source emissions has been recognized as one of several strategies necessary for mitigating release of greenhouse gases into the atmosphere. Power plants that generate electricity from carbon based fuels may be required to separate CO_2 from flue gas streams. Chemical routes to hydrogen production from coal and natural gas can be enhanced with CO_2 separation. This would be simplified with the availability of high temperature CO_2 selective membranes.

To extract CO_2 from a process stream without first cooling and later reheating the remaining fuel rich stream for recirculation would represent a major improvement in efficiency for any advanced power technology using CCS.

Researchers demonstrated the proof of concept of a novel dual-ion conducting membrane to separate CO_2 from other gases in the temperature range 600° to 850° C. A commercially viable membrane device would need to be mechanically simple, low cost, and have low parasitic energy losses while separating CO_2 from process or flue gasses at a level that is competitive with current CO_2 capture technologies. Availability of such membranes could open the door to innovative power plant schemes. Figure 12 illustrates the concept.

Figure 12: Concept Diagram of CO_2 Flux in Membrane



2.9.3 Objectives

The goal of this project was to determine the feasibility of selectively separating CO_2 at temperatures greater than 400° C using a dense dual-ion conducting membrane. The researchers established the following project objectives:

1. Demonstrate helium permeance < permeance through a porous membrane and demonstrate helium permeance does not increase after cooling and reheating.
2. Demonstrate CO_2 permeance > 10x helium permeance within 400°—1000° C.
3. Demonstrate CO_2 permeance is > 10x CO, H_2, N_2, CH_4, H_2O, or O_2 permeance.
4. Confirm CO_2 permeance will increase with decreasing membrane thickness.
5. Confirm CO_2 selectivity is unchanged or decreasing with decreasing membrane thickness.
6. Confirm decreasing solid oxide pore size increases CO_2 permeance.
7. Confirm decreasing solid oxide pore size increases CO_2 selectivity.
8. Find alternative membrane materials and test the chemical reactivity.

2.9.4 Outcomes

1. The researchers fabricated composite membranes with low helium leak rates. They measured over two orders of magnitude decrease in helium leakage once the molten salt melted into the solid oxide pore space. The researchers observed leaking above 800° C but determined the cause of the high temperature leak was delamination of the ceramic seal.

2. The researchers measured CO_2 permeance that was 10 times greater than that of helium at 750° C using early test membranes.

3. The researchers measured CO_2 selectivities of 11, 24, and 60 with He, CH_4, and CO, respectively, at 750° C.

4. The researchers showed CO_2 permeance was inversely proportional to membrane thickness. This suggested the rate of CO_2 transport was limited by transport within the bulk membrane material. The researchers measured permeance as a function of porosity but the results were inconclusive.

5. The researchers measured dependence on porosity. The results were inconclusive.

6. The researchers found CO_2 permeance was inversely proportional to membrane thickness.

7. The researchers measured dependence on porosity. The results were inconclusive.

The researchers observed irreversible reactions between lithium carbonate and yttria stabilized zirconia (YSZ). They observed reversible chemistry with a tertiary mixture of carbonates and YSZ. There was no observed reactivity between sodium or potassium carbonates with YSZ. They observed no reactivity with any of the alkali metal carbonates and a second oxide electrolyte, gadolinia doped ceria (CGO). They found successful CO_2 permeance with membranes comprising YSZ and a bi-mixture of sodium and potassium carbonates. The lack of reactivity measured with TGA/XRD analysis did not hinder the transport mechanism. Reactivity observed with lithium carbonate melts proved detrimental to the lifetime of the membrane. Membranes comprising YSZ and lithium carbonate exhibited lifetimes under 36 hours and failed due to formation of lithium zirconate. CGO based membranes with a tertiary mixture of carbonates successfully permeated CO_2. Alumina based membranes, a non-oxide conducting ceramic, permeated very little CO_2. This provided evidence for the significance of the solid oxide phase.

2.9.5 Conclusions

The researchers demonstrated proof of concept of high temperature selective removal of CO_2 using membranes. Membranes constructed of alkali metal carbonates and gadolinia-doped ceria appeared most promising based on in-cell degradation reactions, lifetime, and permeability compared to other membrane materials evaluated. Ceramic edge sealing is problematic for future design consideration, as would be the case in any configuration using materials with differing thermal expansion coefficients. Membranes using alkali metal carbonates are likely to be degraded when exposed to high temperature gas streams containing acid gasses (e.g., NO_x or

SO_x) and should be only considered for application downstream of post combustion NO_x or SO_x control equipment.

2.9.6 Recommendations

New membrane materials and modification of the membrane microstructure should be researched further.

Stability of the membrane in harsh fuel gas atmospheres needs to be addressed. In particular, stability in the presence of steam is critical, as it will be the likely sweep gas to pull CO_2 away from the permeate surface. The researchers should also explore the tolerance of these membranes with respect to stronger acid gas species, such as H_2S. They should investigate and develop the mechanical design of the membrane device. Improvements in sealing would help with overall selectivity while increasing membrane surface area per unit volume.

The researchers should publish technical papers outlining the proof of concept to raise awareness of the concept.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.9.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

1. Reduced environmental impacts of the California electricity supply, transmission, or distribution system
2. Increased public safety of the California electricity system
3. Increased reliability of the California electricity system
4. Increased affordability of electricity in California

The primary benefit to the ratepayer from this research would be reduced environmental impacts of the California electricity supply system. A secondary benefit would be reduced costs by virtue of increased thermal efficiency for power plants and other facilities employing carbon capture.

The major drawback of solvent scrubbing is the cost due to the high energy requirements of the process. The energy required using monoethanolamine (MEA) as a solvent (the most developed

technology) can cause a 20 percent reduction of power generation for a coal fired facility.[38] Addition of an amine scrubbing CO_2 capture plant would reduce efficiency by 21 percent to 36 percent due to cooling and then reheating both the solvent and flue gas. The concept that was subject of this research should significantly reduce the efficiency penalty compared to amine based carbon capture, regardless of whether the fuel source is coal or natural gas.

In 2008 California generated 122,000 GWh of electricity using natural gas. If this concept were successfully applied to all current natural gas fired facilities, an additional 21,000 to 44,000 GWh would be available with no increase in natural gas use compared to amine based capture technology. A reasonable penetration achievable in 15 years might be 10 percent of then existing capacity or the equivalent of 2,100 to 4,400 GWh.

2.9.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.9.8.1 Marketing/Connection to the Market

At the conclusion of this project the researchers were looking for industrial partners who could help them take resulting products to market.

2.9.8.2 Engineering/Technical

The researchers plan to improve sealing and surface area optimization. Their goal is to improve the flux of CO_2 and widen the temperature range over which the membrane is functional. They stated the engineering work necessary to define a product could take five years. The researchers are seeking additional funding to continue their work.

2.9.8.3 Legal/Contractual

The researchers applied for and have been assigned Patent WO2006113674 (A2).

2.9.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

No quality plans and assessments are included in the ongoing engineering work.

2.9.8.5 Production Readiness/Commercialization

The researchers stated the project requires advances on the pre-competitive research level before moving to a business plan.

2.10 Dynamic Analysis Tool Development for Advanced Geometry Wind Turbine Blades

Awardee: Scott Larwood

Principal Investigator: Scott Larwood

38 http://www.iea-coal.org.uk/site/ieacoal_old/publications/newsletter/current-issue-a/newsletter-3?

2.10.1 Abstract

The goal of this project was to develop and validate a new analysis tool for swept wind turbine blades. This project was an outgrowth of research on swept blade design being performed under contract for the United States Department of Energy (USDOE). Because commercially available dynamic modeling applications were cost prohibitive, the researchers proposed modifications to FAST, a public domain application which was originally developed for the National Renewable Energy Laboratory (NREL) for use in analysis of straight blade wind turbines. Code modifications allowed for cost effective, rapid analysis of curved turbine blades. The researchers evaluated accuracy of the new CurveFAST model through comparison to results from the commercially available MSC.ADAMS® dynamic modeling program and limited field testing. Model comparisons revealed good correlation in normally evaluated parameters, but deviated in others due to modeling strategies. Validation through field testing was significantly limited when cost cutbacks resulted in scope reduction for the USDOE project.

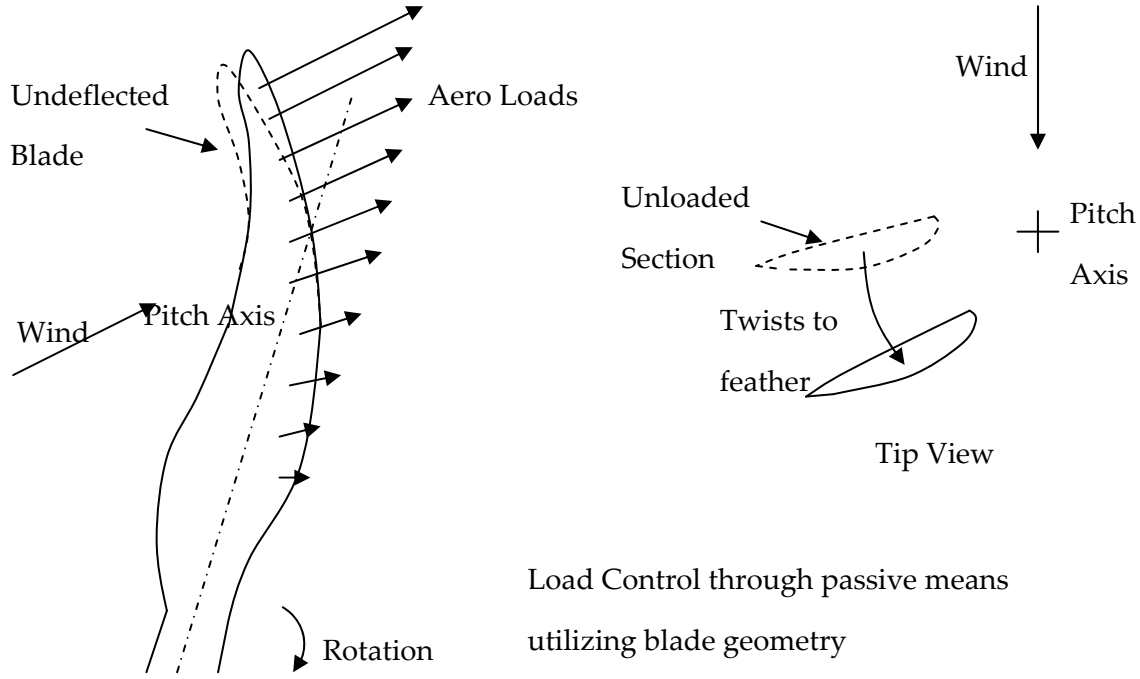
Keywords: Wind energy, wind turbines, wind power, dynamic analysis, rotor blades, sweep

2.10.2 Introduction

Wind turbines are being used more widely in the effort to provide renewable energy sources. In 2005 wind power provided 1.5 percent of California's gross system power for a total of 4,446 million kWh.[39] Until recently, wind turbines relied primarily on straight blades. Wind power production is largely a function of rotor diameter, hub height, and wind speed. Increasing the rotor diameter allows turbines to increase the wind energy potential, particularly in low wind speed conditions. However as the rotor diameter increases, its mass increases with the cube of the diameter. Additionally, an increased rotor diameter causes an increase in stress on the rotor blades. Therefore blades must be lighter and produce less stress to increase rotor diameter without increasing turbine costs. To accomplish this, researchers have begun focusing on swept blade designs such as that shown in Figure 13, which potentially will lower the cost of energy by allowing the rotor diameter to increase without increasing the size of the rotor hub.

39 California Energy Commission, *Net System Power: A Small Share of California's Power Mix in 2005*, 2006. CEC-300-2006-009-F. http://www.energy.ca.gov/2006publications/CEC-300-2006-009/CEC-300-2006-009-F.PDF

Figure 13: Sweep Twist Adaptive Rotor Concept



The researchers in this project participated in a United States Department of Energy (USDOE) project focusing on the swept blade concept. The goal of the USDOE project was to design, construct, and test a wind turbine rotor that incorporated sweep into the blade geometry to increase energy capture for a given state of structural loading.[40] Researchers used the commercial MSC.ADAMS® dynamic modeling program under academic license during initial concept work on the USDOE project. However further development of the concept work necessitated acquisition of a commercial license, which was cost prohibitive to the project. Use of the MSC.ADAMS® program also hindered efforts to perform rapid design evaluation, as each design iteration took 3.5 hours to complete. The research proposed would provide a cost effective public domain analysis tool capable of relatively rapid simulation runs.

A literature review performed as part of the USDOE project revealed few publications and software applications that could be applied to the swept blade design.

The researchers identified MSC.ADAMS®, a dynamic modeling application used for the aerospace and automotive industries, as the tool with the most flexibility to model swept blades, but it was cost prohibitive for research applications, with licensing costs totaling

40 Knight & Carver, *Sweep-Twist Adaptive Blade Design Project Overview*, 2006. http://www.sandia.gov/wind/2006BladeWorkshopPDFs/GaryKanaby.pdf

$32,000. Other commercially available applications developed specifically for the wind turbine industry include the following:

1. FAST, a National Renewable Energy Laboratory (NREL) public domain application developed by Oregon State University
2. Bladed, a commercial application developed by Garrad Hassan of the United Kingdom
3. FLEX5, a commercial application developed by Stig Øye of Denmark.

Licensing costs for Bladed were 25,000 pounds, even more cost prohibitive than MSC.ADAMS®. FLEX5 costs were unavailable.

The researchers chose to modify NREL's FAST application, since it was the only alternative with public domain code. Code modifications included the following tasks:

1. Add a new coordinate system for new blade geometry.
2. Develop equations of motion in the new coordinate system.
3. Develop blade mode shapes for the new blade geometry.

Details of the code modification required for the new analysis software (which the researchers called CurveFAST) are included in Appendix I of the Final Report of this project.

Upon completion of code modifications, the researchers proposed to validate CurveFAST output through comparison to MSC.ADAMS® modeling results and field testing. Normal test parameters, including flap and edge bending, and generator power were within 5 percent agreement with MSC.ADAMS® modeling results. However, most other parameters exceeded 5 percent difference, with the maximum tip twist 145 percent less for CurveFAST than for MSC.ADAMS®. Field testing proposed was not completed due to budget constraints for the related USDOE project. The researchers used CurveFAST to show that the swept blade concept could be scaled for larger turbines.

2.10.3 Objectives

The goal of this project was to develop and validate a new analysis tool for swept wind turbine blades. The researchers developed this tool as an outgrowth of research on swept wind turbine

blades being performed for the USDOE. The goal of the USDOE project was to achieve a 5 percent increase in annual energy capture with an associated decrease in the cost of energy through the use of a swept blade configuration rather than the traditional straight blades. The researchers established the following project objectives:

1. Demonstrate that the new software does not increase run time by 50 percent over the original code.
2. Demonstrate that a model of the swept blade in the new software agrees with commercially available MSC.ADAMS® dynamics code to within ±5 percent.

3. Demonstrate that blade accelerations measured in the field test are accurate to within 5 percent.
4. Demonstrate that the model of field test turbine in the new code agrees within ±10 percent.
5. Maintain a 5 percent annual energy capture improvement when scaling the swept blade to larger rotors.

2.10.4 Outcomes

The first working and verified version of CurveFAST took 55 percent longer to run than the baseline FAST iterations. The researchers modified the code for a second version, which resulted in run times that were 48 percent longer than the baseline.

Verification runs performed for MSC.ADAMS® agreed to within 5 percent over much of the operating range, but not for blade twist, deflection, and peak bending loads at rated power. The researchers presented percent difference between the two models in Table 5 of their Final Report, with values ranging from 2.8 to 145 percent.

This task was not performed due to scope reduction in the USDOE project.

The researchers collected field test data in wind speeds ranging from 2 to 16 m/s as measured by the nacelle anemometer. They did not measure actual ambient wind speed, but it was likely smaller due to the presence of the turbine wake. The researchers performed five 10-minute simulations at each wind speed. They showed comparisons graphically for generator power, blade pitch, root edge bending, and root flap bending. Researchers did not tabulate percent differences for each parameter, but included a discrepancy of 14.1 percent between CurveFAST and field data for peak edge bending loads.

The researchers performed parametric studies using CurveFAST to analyze the effects of varying blade torsional stiffness, amount of tip sweep, and the value of the sweep curve exponent under wind speeds which varied from 3 to 25 m/s. They computed the annual energy production and damage equivalent loads under the various scenarios. They obtained baseline parameters using WindPACT for turbines with 1.5 MW and 3.0 MW power ratings and then scaled for swept blades by increasing the rotor diameter by 25 percent. The researchers performed a number of analyses and optimizations on the scaled rotor design including optimal pitch, tip speed ratio, power coefficient, turbulence, and flutter. The percent annual energy production over baseline was 5.0 percent and 5.1 percent for the 1.5 MW and 3.0 MW turbines, respectively.

2.10.5 Conclusions

The researchers met the objective to limit CurveFAST run times to less than 50 percent more than FAST run times. Total run time for CurveFAST was 66 minutes, significantly less than 3.5 hours required to run MSC.ADAMS®. This would allow significantly faster iteration for design and research applications.

The researchers did not meet the object to show output agreement with MSC.ADAMS® within 5 percent. They concluded that results differences were due to the lumped parameter approach used by MSC.ADAMS®. They reached this conclusion based on Figure 8 in the Final Report, which showed the twist degree of freedom has higher amplitude than the CurveFAST application for the first flap bending mode. Data presented in the report did not support this hypothesis, but was the basis for further research proposed by the investigators. The researchers also noted that the large disagreement reported as a percentage was in part due to small absolute values reported and used to obtain the percentage. Data analysis did not include suggestions of which portion of the operational range that CurveFAST appeared to be most accurate when compared to MSC.ADAMS®.

The researchers did not meet the objective to validate blade accelerations during field testing.

The researchers did not meet the objective to validate CurveFAST using field testing. They concluded the discrepancies in edge-bending were likely due to uncertainties in the blade structural properties. Input parameters were not well known because of lack of field test measurements. Field conditions that were either unknown or estimated included: ambient wind speed, torque-speed relationship, and blade pitch behavior. Additionally, the model did not include peak edge and flap loads. The number of unknown variables prevented validation through field testing.

The researchers met the objective to scale the swept blade design to larger rotors while maintaining at least a 5 percent annual energy capture. The new designs increased annual energy production by 5 percent with a potential for decreased fatigue loads.

2.10.6 Recommendations

Although the researchers were unable to validate the CurveFAST tool to the tolerances proposed through field testing and model comparison, CurveFAST appears to be valuable in terms of cost and speed of analysis. The researchers recognized the need to continue validation efforts and suggested enhancements prior to incorporation into NREL's existing FAST model. Although the researchers did not intend to continue development of CurveFAST, Knight and Carver, the investigators for the USDOE project, are pursuing the technology. As part of continued development of this technology, the Program Administrator recommends that the following tasks be completed:

1. Complete validation efforts to original project objectives using field and model studies.
2. Investigate model enhancements described in the recommendations section of the Final Report.
3. Identify potential commercialization partners (Knight and Carver, for example) that can champion incorporation of the CurveFAST code module into NREL's FAST.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.10.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

Reduced environmental impacts of the California electricity supply, transmission, or distribution system

1. Increased public safety of the California electricity system
2. Increased reliability of the California electricity system
3. Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. The researchers included calculations showing a $5 M annual savings to California (based on 2005 data) by using the swept blade design. However research contained in this project pertains only to use of CurveFAST as an alternative to commercially available modeling tools in the analysis of swept blade designs. Under a best case scenario, the CurveFAST application could become a public domain tool provided free of charge by NREL. In this case, the public benefit would be the cost savings of the alternative commercial modeling tool for each installation used. Alternative commercially available modeling tools identified as part of this study range in cost from $32,000 to approximately $40,000. Time savings provided through the use of CurveFAST in rapid design applications are also applicable, but more difficult to quantify.

2.10.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.10.8.1 Marketing/Connection to the Market

The researchers have not performed a market analysis. This technology is primarily applicable to utilities, but may be scaled for residential wind turbine designers.

2.10.8.2 Engineering/Technical

The researchers do not plan to pursue commercialization, but do not foresee any technical or engineering obstacles.

2.10.8.3 Legal/Contractual

The concepts and application coding are public domain and are thus not patentable.

2.10.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

The technology pertains to an analysis methodology and will not require environmental, safety, risk assessment/quality plans. Additional research with field and model validation will test quality control of the methodology.

2.10.8.5 Production Readiness/Commercialization

The researchers do not plan to pursue commercialization, but note that Knight and Carver and General Electric are already pursuing the concept.

2.11 Feasibility Evaluation of a Direct Carbon Fuel Cell Operating on Petroleum Coke Using Molten Carbonate Electrolyte

Awardee: Gas Technology Institute

Principal Investigator: Chinbay Fan

2.11.1 Abstract

California has a large amount of petroleum (pet) coke that is a byproduct of the crude oil refining process. The pet coke is produced at an annual rate of about 12 million tons. Assuming that two thirds of the pet coke has appropriate qualities and is available for power generation, the energy content is sufficient to supply fuel to power plants with a total capacity of 2000 MW. The challenge for California is to produce that amount of power without a negative effect on the environment. Because most California pet cokes are low in ash and sulfur, they may be suitable as a fuel in direct carbon fuel cells (DCFC). Fuel cells have extremely low emissions.

This project proposed to use modified molten carbonate fuel cell (MCFC) designs, carbonate wetted carbon fuel (petroleum coke), and CO gas to simulate a direct carbon fuel cell (DCFC). The overall objective of the project was to improve power density and endurance compared to the DCFC designs available at the start of this project.

The researchers pre-wetted both petroleum coke and graphite samples with a lithium/potassium (Li-K) carbonate eutectic. They found the coatings to be uniformly distributed on the carbon surface. They used modified MCFCs to test the pre-wetted fuels. The researchers developed an elutriation method that allowed carbonate pre-wetted carbon to be introduced into an essentially unmodified MCFC cell. Elutriation-fed cells failed early in their operation due to component failure that the researchers believed to be unrelated to use as a DCFC or the elutriation method of fuel feed.

Keywords: Environmentally preferred advanced generation, direct carbon fuel cell (DCFC), molten carbonate fuel cell (MCFC), carbon oxidation, carbonate, petroleum coke, pet coke

2.11.2 Introduction

The California energy problem addressed in this project was utilization of the large amount of petroleum (pet) coke that is a byproduct of the crude oil refining process. Most California pet cokes are low in ash and sulfur, making them suitable for direct carbon fuel cells (DCFC). Pet coke is produced at an annual rate of about 12 million tons and is mostly exported to Asia for

power generation in coal-fired power plants. Current combustion methods of pet coke in Asia result in high levels of air emissions and carbon dioxide.

The benefits to California ratepayers, if the feasibility of the improved DCFC were proven, would be to convert the approximate 2,000 tons of pet coke per day produced from a typical oil refinery into electricity. This quantity would support a power plant with a capacity of approximately 200 MW. Assuming two thirds of California's pet coke (eight million tons per year) is available as fuel for DCFC power plants, a total of more than two gigawatts of capacity (ten 200 MW plants) could rely on this fuel. According to a recent California Energy Commission report[41] the electric power generation capacity of the state is approximately 58 GW.[42] Pet coke-fueled power plants could provide over 3 percent of its electricity. In addition, pet coke utilization in California eliminates the need to transport this material. Transportation fuel is saved, and truck, train, and ship air emissions eliminated.

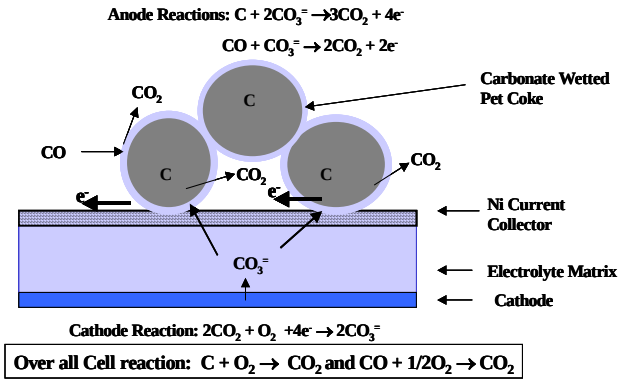
The advancement of science or technology that was proposed in this project was to prove the feasibility of a molten carbonate fuel cell (MCFC) based DCFC concept that incorporated advances in MCFC technology, carbon monoxide oxidation, and oxidation of carbonated wetted pet coke fuel to obtain commercially promising performance and endurance. The potential performance improvements include an increase in the fuel cell direct current (DC) electrical efficiency to about 80 percent (assuming 0.8 voltage efficiency and 750° C operation). This compares to 45 percent for hydrogen fuel cells (on the same basis) due to the favorable entropy change of the carbon reaction and the high utilization possible with a constant activity carbon reactant. Figure 14 illustrates the proposed DCFC concept. The performance goal was 200 mW/cm^2 power density at 0.7 V for up to 200 hours at 750˚C.

The DCFC operation begins when pre-wetted pet coke is introduced to the anode with the aid of CO_2 carrier gas. Prior to entering the cell, the anode feed stream is pre-heated, and CO_2 is partially converted to carbon monoxide (CO). The pre-wetted coke forms a porous network of percolated (continuous) particles for efficient transport of reactants and products. In the anode, both CO and carbon react with $CO_3^=$ from the electrolyte to form CO_2 and electrons. The electrons are conducted back into the cathode through the external circuit.

41 Brown et al, 2008.

42 http://www.netl.doe.gov/technologies/coalpower/fuelcells/publications/fuelcell/fc-cleanup/Gasification percent20Plant percent20Cost-Perf percent20Optimization_9-01-03.pdf

Figure 14: GTI's DCFC Concept



The excess carbonate brought in by the pre-wetted coke is siphoned out of the active components by a wick to maintain a balanced carbonate distribution among the active components. The increased cell performance is expected to come from the potentially lower polarization of the CO oxidation pathway.

2.11.3 Objectives

The goal of this project was to determine the feasibility of a direct carbon fuel cell (DCFC) concept using petroleum coke to produce clean electricity. The technical challenge was to increase power density and overall performance. The researchers established the following project objectives:

1. Obtain pet coke samples from suppliers with low sulfur (~0.1 percent) and ash contents (~0.1 percent).
2. Determine samples' sulfur and ash contents, particle size, surface area, bulk and tap density, and morphology.
3. Pre-wet pet coke to have a carbonate coating of about 0.5 μm thick.
4. Assemble and test two, three, or four 100 cm^2 bench scale DCFC of the proposed conceptual design.

2.11.4 Outcomes

A.J. Edwards provided the California pet coke sample for this project's DCFC evaluation. The sample was produced from premium grade crude and was being produced at an annual rate of 650,000 metric tons, which is sufficient for supporting future technology development and demonstration.

The researchers analyzed pet coke samples according to standard ASTM procedures. Although the sulfur (1.0 percent) and ash (0.32 percent) contents were low for pet coke standards, they were still higher than the targets of 0.1 percent sulfur and 0.1 percent ash. Therefore graphitized pet cokes were obtained from TimCal and analyzed according to standard ASTM procedures.

These graphitized samples had the high purity and controlled particle size required for the baseline DCFC evaluation.

The researchers pre-wetted the pet coke and graphite samples with carbonate to obtain the intended fuel feed for DCFC. The carbonate was 10 volume percent of the mixture and had a eutectic composition of 62Li/38K. SEM and EDS analysis of the wetted samples showed uniform carbonate distribution.

The researchers operated four bench scale (100 cm^2 active area) DCFCs with the intention of first identifying key issues in operating DCFCs and then studying effects of various key operating parameters to demonstrate steady high power densities. The first and second cell tests were aimed at determining the effects of major cell operating parameters. The tests revealed that CO_2 was the only reaction product in any case where the carbon was electrically in contact with the anode. When there was inadequate electric contact with carbon, the researchers observed CO formation. Overall cell performance was poor in all cases tested, but the researchers made several important observations. An area of significant difficulty was fuel cell design to allow a solid fuel to be used. Any design modification had to ensure good electrical contact between both anode and cathode current collectors and the matrix. In these efforts the contact issue was avoided by developing an elutriation method to supply carbon to the cell, which allowed the cell to be operated without design changes from the standard MCFC. Unfortunately, component failure compromised the results of these efforts. Even in cases where there was poor electrical contact, the researchers observed some changes in oxidation kinetics and temperature dependence of oxidation for different carbon types.

2.11.5 Conclusions

This work showed that it is possible and relatively simple to produce a thin, uniform coating of carbonate on a variety of carbons. The researchers successfully used carbon coated in this way as a fuel source in a DCFC. They showed that carbon oxidation to CO_2 increased with current load. Oxidation was also shown to be complete when good electrical contact with the carbon was made. When contact was incomplete CO formation also occurred, as expected from the Boudouard reaction. However the power densities observed in this work were very low. The approach of loading the carbon fuel into the anode gas channels hindered mass transfer and prevented convincing demonstration of the proposed DCFC concept. The researchers showed elutriation to be a reasonable carbon supply technique. However issues preventing a steady stream of carbon supply to the fuel cell remained.

Researchers also tested carbonate coated California pet coke as fuel. It also oxidized to CO_2 under load. However, due to low load and short test duration, the researchers could not assess its compatibility with the DCFC.

While the researchers produced and tested four cells, early failure prevented proof of concept.

2.11.6 Recommendations

The researchers stated that they did not prove the feasibility of using DFCF to produce electricity at improved rates from pet coke. Rather, they discovered several key bottlenecks and problems that needed to be solved prior to achieving successful operation of the fuel cell using

pet coke. In this sense the project produced useful results, which lead to the following recommendations:

To further advance the technology, several technical problems need to be overcome. First, a better understanding of the controlling factors of carbon oxidation rate needs to be developed. Specifically, carbon oxidation under electrochemical oxidation in the presence of molten carbonate needs to be more thoroughly understood. This work was probably best done in small laboratory scale cells that do not require machining and special designs to deal with the introduction of carbon to the system.

Another area identified in this work that requires attention was the feeding of the solid carbon fuel. Initial results presented here with elutriation of carbonate coated carbons appeared promising, but the work was in its early stages. Developing proven technology capable of consistently delivering fuel to the cell without causing clogging or dead spots in the cell active area are critical to the commercial viability of any DCFC technology. Further studies need to optimize the carbon feed size, morphology, carbonate content, and residence time (or percent utilization). Again, they would be more economically addressed in laboratory scale cells.

2.11.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

1. Reduced environmental impacts of the California electricity supply, transmission, or distribution system
2. Increased public safety of the California electricity system
3. Increased reliability of the California electricity system
4. Increased affordability of electricity in California

The primary benefit to the ratepayer from this research was reduced environmental impacts of the California electricity supply, transmission, and distribution system. The project goal was

to utilize pet coke from the petroleum refining industry for electrical generation via direct carbon fuel cells. If successful, this process could reduce the environmental impact of the air quality and greenhouse gas concerns of combusting the high carbon content pet coke, while providing additional clean electricity for California. However the project did not succeed in proving the concept of efficient utilization of pet coke in a DCFC. There was some progress in developing the process of introducing the solid carbon to the fuel cell, and it appears that with more research the goals might be achieved. The possible benefit to the California ratepayer would be an additional two GW of clean electrical power from eight million tons per year of pet coke, an approximate 67 percent market penetration. Although this research project was operated in a professional manner, the extremely difficult problems of introducing carbon to fuel cells from a materials handling perspective indicate limited hope for this concept to

succeed. The process of an integrated gasification combined cycle followed by sequestration of the CO_2 appears to be a better method of utilizing petroleum coke.[43]

In February 2009 the California Public Utilities Commission (CPUC) Commissioner Michael Peevey said[44] that the state is embarking on the world's first gasification and carbon sequestration project to use petroleum coke from oil refineries to produce clean electricity. The CPUC directed Southern California Edison Company to fund Phase I of a study to utilize pet coke in an integrated gasification combined cycle. The CPUC project promises benefits similar to those of this EISG project. Both approaches have merit and both have technical challenges. The Program Administrator estimates that benefits from either approach will not be realized for at least 10 years.

2.11.8 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.11.8.1 Marketing/Connection to the Market

The California Public Utilities Commission has directed Southern California Edison to undertake a $30 million project to utilize pet coke in an integrated gasification combined cycle power plant to produce clean electricity. This demonstrates a strong market/regulatory connection.

2.11.8.2 Engineering/Technical

The qualities of different samples of pet coke vary significantly. Some pet coke samples have sulfur content as high as 6.5 percent, while other samples contain fractional percentages of metals. In general, pet coke has high hardness, which tends to wear out crushers quickly. These properties of pet coke increase the technical challenges of developing a commercial process to utilize pet coke to produce clean electricity.

2.11.8.3 Legal/Contractual

The Program Administrator has not noted any activity in this area.

2.11.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

One safety consideration is the use of carbon monoxide as an additional fuel. In addition, pet coke has been designated as a cancer causing material and must be handled as such. Pet coke often contains large fractions of fine particles. This is both a health risk and a safety risk. These risk factors must be addressed as a process is developed to convert the pet coke into clean electricity

43 http://www.eia.doe.gov/electricity/chg_str_fuel/html/chapter4.html

44 http://www.cleantech.com/news/4207/california-attempts-clean-coal-petr

2.11.8.5 Production Readiness/Commercialization

This concept is far from being close to production readiness or commercialization.

2.12 The Next Wave in Air Conditioning: Acoustic Stirling Commercial Rooftop Units

Awardee: CFIC-Qdrive

Principal Investigator: Phil Spoor

2.12.1 Abstract

The goal of this project was to determine the feasibility of a Cascaded Acoustic Stirling Air Conditioning (CASAC) System for commercial rooftop applications. The researchers sought to design a simple device consisting of pieces of foam or stacks of plastic screen sandwiched between oil coolers used as heat exchangers in a cascaded Stirling system. The concept would use low pressure air instead of traditional refrigerants. Simulations led the researchers to conclude that a low pressure air CASAC would not have the necessary power density and would not achieve the required coefficient of performance (COP). Numerous technical setbacks delayed the completion of this prototype, resulting in an incomplete characterization. Efforts in this project suggested that further performance characterization will not show feasibility.

Keywords: Thermoacoustic, Stirling, air conditioning, cascade,

2.12.2 Introduction

Electric consumption in commercial buildings in California currently is about 67 billion kilowatthours (kWh) per year. About 15 percent, or 10 billion kWh, of that electricity use goes to air conditioning.[45]

Even a modest 10 percent improvement in installed efficiency of this equipment would translate to saving over a billion kWh per year, worth $150 million to consumers, and a corresponding reduction of over 1000 MW in peak demand. Computer modeling of the Cascaded Acoustic Stirling Air Conditioning (CASAC) promised up to 15 percent higher total efficiency at lower cost in an environmentally benign, low pressure system that could be packaged as a drop-in replacement for current rooftop air conditioning units.

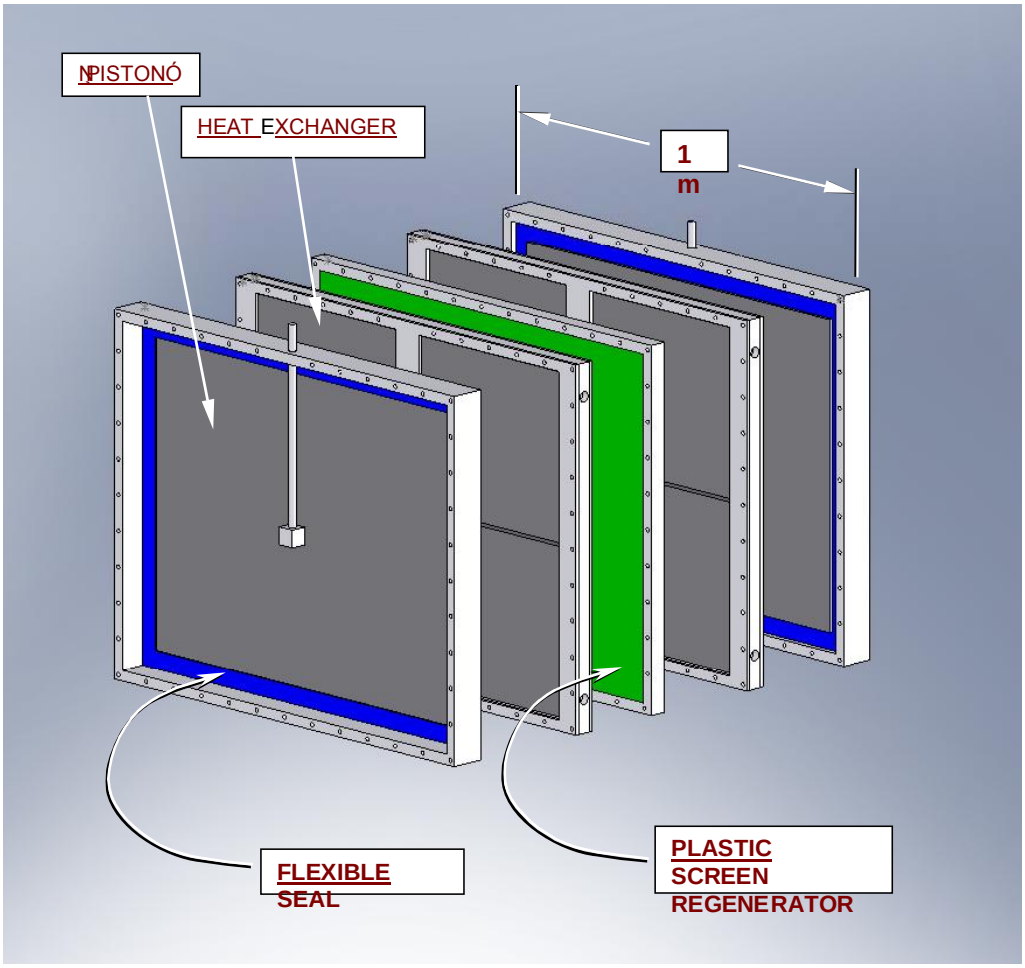
The goal of this project was to determine the feasibility of a Cascaded Acoustic Stirling Air Conditioning (CASAC) System for commercial rooftop air conditioning. This type of heat pump uses air as the working fluid instead of conventional refrigerants, and it has few moving parts. The device consists of a series of small parallel channels, referred to as a stack, fixed in place and surrounded by a created standing acoustic wave, all enclosed by a structure. In a standing acoustic wave, regions of alternating high pressure and low pressure characterize the wave. These regions are thermodynamically similar to the high and low pressure regimes used in

45 Itron, Inc., *California Commercial End-Use Survey*, California Energy Commission

March 2006 CEC-400-2006-005.

refrigeration cycles which create high and low pressure by use of mechanical compressors. Heat can be extracted from high pressure regions and thus be made useful for cooling. This process approximates the mechanics of a Stirling cycle but without the cranks, the sliding seals, or the weight found in typical Stirling engines. Figure 15 shows a mock-up of the stack.

Figure 15: Solid model of low pressure air cycle Stirling core for air conditioner prototype



2.12.3 Objectives

The goal of this project was to demonstrate the feasibility of a Cascaded Acoustic Stirling Air Conditioner intended for widespread drop-in replacement in commercial rooftop use. The researchers established the following objectives:

1. Confirm by simulation that 10 tons of cooling capacity is achievable in one module, with COP greater than 3.0.
2. Confirm by simulation that baseline unit is scalable to 5 kW capacity (approximately 1.5 ton of refrigeration).

3. Demonstrate that the subscale prototype will produce 5 kW cooling capacity as modeled.

4. Demonstrate COP greater than 3.0 per the ASHRAE 90.1 standard. Demonstrate turndown to 25 percent of rated capacity without loss of COP.

5. Demonstrate by analysis unit manufacturing costs in volume within 20 percent of quoted retail price for standard units of the same capacity.

6. Verify effective IPLV per ARI standard 550/590-98, adjusted for modulation, greater than 12.0.

2.12.4 Outcomes

1. The researchers successfully modeled a 10 ton capacity unit, but they deemed its physical size impractical. Because the simulations only provided theoretical first order results and did not account for specific component performance curves, scaling to different sizes provided only trivial results. Modeling using two different models gave widely different results.

2. This objective was partially met. The CASAC as simulated replicated the theoretical Stirling cycle closely. Most of this work centered on simulating the subscale prototype, since for that case there is hardware (e.g., the oil cooler heat exchangers) upon which to base the simulation. The prototype simulation indicated ease of scale up to a 10 ton (35 kW) size. The subscale prototype was modeled to produce 1 kW with a cross sectional area of 1 m^2. However the researchers did not show how to construct a full size unit. The oil cooler type of heat exchanger used in the prototype would not support itself at the size and framework that would be required, complicating design and increasing weight. The researchers estimated a completed size of about 25 feet by 25 feet rather than the originally projected size of three feet by three feet.

3. The researchers established specifications for a 5 kW (1.5 ton) subscale unit by the modeled requirements for a 10 ton unit. They reduced the actual capacity based on commercially available components. The researchers did not complete a specific simulation that corresponded to the original subscale target of 5 kW, as that size proved unfeasible.

4. The researchers curtailed the subscale demonstration. It did achieve operation but no net cooling. The researchers did not demonstrate steady state COP greater than three nor part load turndown. They did not test part load performance because of size and cost results. This objective was not completed. Warm side temperatures were unchanged and cold side temperatures rose slightly. The pumps themselves added some thermal load (heat). This appeared to be a cause of the temperature rise measured on the cold side and failure to produce cooling. This objective was not met.

5. The researchers estimated costs based on the assumption of stacking multiples of the subscale modules together. Cost estimates for production of modules based on the subscale size (largest commercially available heat exchangers) were too high for

commercial interest. The researchers estimated a unit would require 35 core assemblies to deliver 10 tons of cooling capacity for a manufacturing cost greater than $13,000. This concept is not competitive with conventional air conditioning systems where a conventional 10 ton condensing unit retails for $3,000 to $4000. This objective was completed, but the results were not practical.

6. Effective integrated part load values (IPLV) per ARI standard 550/590-98, adjusted for modulation, were not measured. ARI standard 550/590-98 measures the average efficiency under a mixed operating cycle of differing load levels. This objective was not completed.

2.12.5 Conclusions

The researchers did not demonstrate feasibility of the acoustic system concept. Despite promising computer modeling estimates, actual simulations show that a low pressure air CASAC would not have the necessary power density nor would it achieve the required Coefficient of Performance (COP). Numerous technical setbacks delayed the completion of the prototype, so its characterization is incomplete. Efforts in this project suggested that further performance characterization will not demonstrate feasibility. Significant differences in modeling results early in the project using two different models suggested one or the other model or both need refinement.

2.12.6 Recommendations

The researchers should investigate using working fluids other than low pressure air. High pressure air may reduce overall system size but would complicate expected system manufacturing. Other working fluids, such as various freons, would likely improve COP and reduce size but would also complicate design and manufacturability. The researchers, in conjunction with others, should improve the modeled versus simulated performance of models used to estimate ex-ante performance.

2.12.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

1. Reduced environmental impacts of the California electricity supply, transmission, or distribution system
2. Increased public safety of the California electricity system
3. Increased reliability of the California electricity system
4. Increased affordability of electricity in California

The primary benefit to the ratepayer from this research would be from reduced environmental impacts of the California electrical supply and transmission system by reducing overall demand for electricity. Because the researchers failed to demonstrate technical feasibility, no direct public benefits can be expected.

2.12.8 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.12.8.1 Marketing/Connection to the Market

The researchers failed to demonstrate technical feasibility. Therefore characterizing market connection is not appropriate.

2.12.8.2 Engineering/Technical

The Program Administrator is not aware of additional engineering work by the researchers.

2.12.8.3 Legal/Contractual

The researchers failed to demonstrate technical feasibility, so there are no legal or contractual considerations.

2.12.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

Until the technology is demonstrated to be feasible, environmental, risk, and quality plans are premature.

2.12.8.5 Production Readiness/Commercialization

The researchers did not demonstrate the concept's feasibility, and the technology is not ready for commercialization.

2.13 Woven Turbo Wheel as Key Technology for Economical Compact and High Efficient R718 Chiller that Uses Only Water as Refrigerant

Awardee: Michigan State University

Principal Investigator: Elias Strangas

2.13.1 Abstract

The goal of this project was to achieve proof of concept for a low cost, automatically woven, composite turbo impeller with an integrated motor. The impeller was intended for use in R718 chillers which use water as a refrigerant. The researchers used laboratory and simulation studies to investigate the stress state and structural soundness of prototype impellers wound on a modified computer driven mill. The prototypes showed no signs of structural failure within the limits of the test equipment capability. Simulation studies suggested that the impellers should tolerate tip speeds of greater than 350 meters per second (m/s). The researchers demonstrated impellers that met the goals of weight, cost, and adaptability. Although research did not include implementation of the impellers in a compressor, this technology shows promise as a suitable replacement for titanium impellers in R718 chillers.

Keywords: Water, R718, woven turbo impeller, chiller, filament winding, efficiency, induction motor, integrated motor

2.13.2 Introduction

Refrigerants used in residential and commercial chillers can have negative effects on the environment when released in an uncontrolled manner. To avoid disposal problems of chiller refrigerants, Europeans have developed a refrigeration cycle that uses plain water as a refrigerant. They call the water R718. The key component of a R718 turbo chiller is the compressor, since water as a refrigerant has some specific features that complicate its application in refrigeration plants with turbo compressors. The R718 cycle works under a coarse vacuum. Since the volumetric cooling capacity of water vapor is very low, large volumes of water must be compressed to a relatively high pressure ratio. The higher pressure ratio requires high compressor tip speeds. To achieve the performance needed in these wheels, the Europeans turned to aerospace technology and materials. The resulting compressor wheels are very expensive, essentially stopping deployment of R718 chillers in the United States.

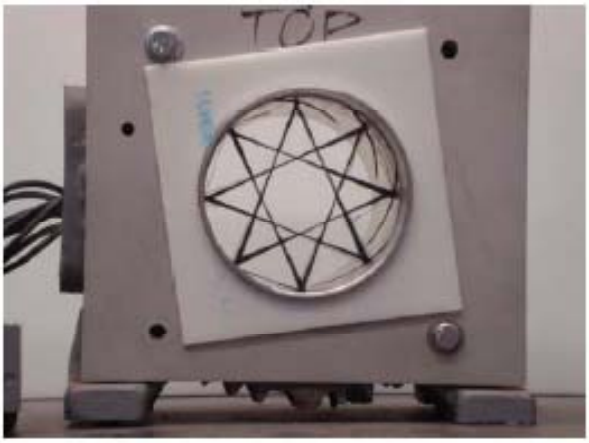
The goal of this project was to prove feasibility of a woven compressor wheel for a chiller that uses water (R718) as a refrigerant. Benefits of water as a refrigerant include, but are not limited to the following:

1. Abundantly available, eliminating the need for manufacturing, refining, or storage capacity
2. Non-toxic and non-flammable, reducing safety concerns and liability risks
3. Low cost
4. Compatible with all current and anticipated environmental restrictions and standards
5. No incremental increase in global warming potential (GWP=0)
6. No incremental increase in ozone depletion potential (ODP=0)

However, water presents technical challenges due to its high boiling point at ambient pressure and high compression ratio when compared with alternative refrigerants used in compressors. Consequently, very high tip speeds are needed to make an R718 compressor viable. Jet engine and gas turbine technologies have been applied to R718 compressors, but the cost, weight, and size of the mechanical components have inhibited adoption of the technology in a residential environment. Some commercial R718 chillers are in production in Europe.

The researchers proposed to reduce drastically the cost of an R718 compressor by replacing the titanium or composite impellers with woven, light weight, high strength turbo impellers with an integrated motor. They performed preliminary design work for an R718 chiller comprised of five rotating wheels forming the compression system. The researchers designed individual wheels to withstand tip speeds of greater than 350 m/s. The two prototype impeller wheels had diameters of 2.5 and 5 inches to accommodate chillers with 3 ton or 10 ton capacities, respectively. They simulated stress states by varying the inner diameter, star pattern density, fiber density, and shroud configuration to optimize the prototype designs. The 2.5 inch impeller had an integrated motor with axle, whereas the 5 inch impeller had none, as shown in Figure 16.

Figure 16: Smaller (2.5 Inch) Woven Impeller with Integrated Motor and Axle (Left) and 5 Inch Woven Impeller without Axle (Right)



Cost analyses of the woven impellers indicated that each impeller could be manufactured for approximately $11, significantly lower than the $50,000 cost associated with current R718 chiller impellers. This significant cost savings could lead to adoption of R718 chillers for residential usage. The researchers stated the use of R718 chillers could lead to a 30 percent energy savings over current technology, which translates to a yearly cost savings of $568 million and a reduction of 6.3 million tons of CO_2 emissions in the State of California.[46,47]

2.13.3 Objectives

The goal of this project was to prove feasibility of a low cost, automatically woven composite turbo impeller with an integrated motor. The impeller was intended for use in an R718 chiller. The researchers established the following project objectives:

1. Design a compact compressor suitable for an R718 chiller, demonstrating that no more than five rotating wheels are needed in the counter-rotating compression system and that the wheel design can withstand tip speeds of greater than 350 m/s.
2. Demonstrate the feasibility of winding such compressor wheels on a commercial winding machine and demonstrate that such composite turbo impellers for a chiller with greater than three ton capacity can weigh less than 1 kg.

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46 BINE Informationsdienst, Germany. 2003. "Wasser als Kältemittel (water as a refrigerant)," projektinfo 08/03, http://www.bine.info/fileadmin/content/Publikationen/Projekt-Infos/2003/Projekt-Info_08-2003/projekt0803internetx.pdf

47 Brown, D. 2003. *Summer 2006 Electricity Supply and Demand Outlook*. California Energy Commission, p 26.

3. Demonstrate that such wound/woven turbo impeller with a diameter suitable for a greater than three ton chiller can withstand tip speeds of greater than 350 m/s.
4. Demonstrate in a design that motor rotor elements can be integrated in the wound/woven turbo impeller suitable for a chiller in the range of 1–10 ton and that it can be driven to tip speeds of greater than 350 m/s.
5. Demonstrate the feasibility of integrating motor rotor elements (for example, magnetic powder or magnetic wires or induction wires) during winding of such impeller wheel on a winding machine and demonstrate that such composite turbo impeller with integrated motor rotor elements for a greater than three ton chiller can weigh less than 2 kg.
6. Demonstrate that the motor rotor elements integrated in a test impeller during winding can drive the impeller at speeds greater than 20 rpm.
7. Demonstrate in a cost analysis that for in large numbers of impellers the manufacturing costs per wheel can be $50 or less.

2.13.4 Outcomes

1. The researchers claimed they performed analytical and computational fluid dynamic (CFD) modeling that showed a five stage impeller design can generate a sufficient pressure rise for an R718 chiller. The researchers did not present the results of those studies. They did present parametric modeling studies in which stress patterns were analyzed as a function of inner diameter, star pattern density, fiber density, and shroud configuration.
2. Researchers produced two impeller prototypes using a modified computer numerical control (CNC) milling machine stage rather than a commercial winding machine. The diameters of the prototypes were constrained by the size of the CNC stage, but included 2.5 inch and 5 inch diameter designs, suitable for a cooling capacity of 3 tons and 10 tons, respectively. The impellers weighed approximately two ounces each.
3. The researchers conducted several speed trials using an air turbine drive. Although the air turbine drive was rated at 65,000 rpm, it lacked the power to exceed approximately 6,500 rpm under load with the prototype impeller. The researchers reported that they successfully completed numerical analyses to compensate for the laboratory testing deficiency in achieving 350 m/s, although results of these analyses were not presented. The researchers did not identify which of the two prototypes was tested. However photographs appear to include the five inch diameter prototype.
4. The researchers stated they designed impellers using a conductive mandrel to operate in an induction machine as part of design work performed for Objective 1. Another design included the addition of magnetizable powder to the resin bath while winding for use in a permanent magnet motor. Design details, specifications, and analyses were not presented.

5. Researchers used an aluminum mandrel while winding for use in an induction machine on what appeared to be a five inch impeller. Additionally, they added iron powder to a resin bath and applied it to the impeller. The completed impeller weighed 64 grams.

6. Researchers tested two bearing schemes, including one impeller with an axle and one without, driven to speeds of 6,000 and 10,000 rpm, respectively.

7. Researchers conducted cost analyses. They included material, labor, and equipment in mass fabrication of the woven impellers. Researchers determined unit costs at $10.80.

2.13.5 Conclusions

1. Results presented are not sufficient to validate whether the researchers adequately met the objective to complete a preliminary design that would generate sufficient pressure for an R718 chiller. Although they presented some modeling results that focused on optimizing the design of an individual impeller based on stress state, none of the results related to pressure generation of the R718 refrigerant when multiple impellers were present. There were no data presented to support the five impeller preliminary designs selected. Although the stress state of the impeller design was simulated, the researchers did not directly relate the stress tolerances and adequacy of the design selected to the capability of the impeller to withstand a tip speed of greater than 350 m/s. Note that bench testing of the impellers under rotation was presented as part of Objective 3.

2. The researchers met the objective to demonstrate the feasibility of prototyping the impellers. Although the proposed manufacturing equipment was not used in completing this task, one can reasonably presume that the winding capabilities could be reproduced on a commercial winding machine. Although the researchers noted that the impeller sizes were constrained by the CNC stage used to create them, it is unclear how the 3 ton and 10 ton cooling capacities were associated with the resultant prototypes. The researchers did not present data to support the relationship between impeller diameter and cooling capacity. Both prototypes were well under the proposed weight objective.

3. The researchers did not meet the objective to demonstrate that the impeller could withstand tip speeds of greater than 350 m/s. If they tested the five inch diameter prototype, laboratory testing achieved only 43 m/s. Researchers did not present numerical analyses, and thus this objective could not be evaluated.

4. Results presented were not sufficient to validate whether the researchers adequately met the objective to design for integration of motor rotor elements. However the researchers were able to successfully prototype some of the design elements as part of Objective 5.

5. The researchers met the objective to integrate motor rotor elements into the impeller. Speed testing was included under Objective 3. The weight of the prototype was well within the objective of less than 2 kg.

6. The researchers met the objective to drive the impellers with integrated motor rotor elements to greater than 20 rpm.

7. The researchers met the objective to demonstrate a manufacturing cost of less than $50 per impeller wheel.

2.13.6 Recommendations

Although the researchers provided insufficient data to validate that all objectives were met, the woven impellers demonstrated a significant cost savings over current technology. The researchers recognized the need for continued research leading toward integration of the impellers into a chiller prototype. As part of continued development of this technology, the Program Administrator recommends the following tasks be completed:

1. Document design, modeling, and testing results to support validation of objectives.
2. Using scientific principles, justify 350 m/s as a performance objective to generate sufficient pressure in an R718 chiller.
3. Repeat bench testing at 350 m/s using higher capacity equipment. Conduct fatigue/failure testing.
4. Document the relationship between impeller diameter and chiller capacity.
5. Identify scientific studies (not government produced information pamphlets) justifying the 20 percent energy reduction that may be realized using R718 technology.
6. Justify the additional 10 percent savings presumably achievable using the technologies presented.
7. Prepare detailed impeller manufacturing specifications.
8. Design and test a chiller prototype with the integrated woven impellers.

2.13.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

1 Reduced environmental impacts of the California electricity supply, transmission, or distribution system

2 Increased public safety of the California electricity system

3 Increased reliability of the California electricity system

4 Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. The researchers stated that the use of R718 chillers could lead to a 30 percent energy savings over current technology, which translates to a yearly cost savings of $568 million and a reduction of 6.3 million tons in CO_2 emissions in the State of California, assuming a market

penetration of 10 percent and reported 2006 usage data.[48] The 30 percent savings was reportedly comprised of a 20 percent savings by using R718 over conventional refrigerants,[49] as well

as a 10 percent savings, with the improved technology resulting from the project design elements including curved blades, outer shroud, axial compressor, and counter rotation. The 20 percent savings was presented as part of a non-scientific government information brochure, without reference to scientific justification of the stated savings. The 10 percent savings resulting from project design elements was not addressed nor demonstrated as part of the research presented herein. Thus the quantification of potential savings should be considered speculative.

2.13.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.13.8.1 Marketing/Connection to the Market

The researchers have not performed a market analysis. This technology is applicable to residential and commercial chiller installations but can be extended to the industrial market.

2.13.8.2 Engineering/Technical

There are still technical challenges requiring additional research, including balancing, demonstration under vacuum, and higher speeds.

2.13.8.3 Legal/Contractual

The researchers reported no activity on patents pending on the technology.

2.13.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

The technology is not mature enough to have prepared environmental, safety, risk assessment/quality plans.

2.13.8.5 Production Readiness/Commercialization

The researchers plan to pursue commercialization and have identified potential commercialization partners, but the technology has not been adequately tested to be market ready.

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48 Brown, D. 2003. *Summer 2006 Electricity Supply and Demand Outlook*. California Energy Commission, p. 26.

49 BINE Informationsdienst, Germany. 2003. "Wasser als Kältemittel (water as a refrigerant)," projektinfo 08/03, http://www.bine.info/fileadmin/content/Publikationen/Projekt-Infos/2003/Projekt-Info_08-2003/projekt0803internetx.pdf

2.14 High Efficiency and Low Cost Single Phase PFC Converters

Awardee: Rensselaer Polytechnic Institute

Principal Investigator: Jian Sun

2.14.1 Abstract

The goal of this project was to determine the feasibility of applying a new control method to dual boost power factor corrected (PFC) single phase rectifiers to achieve 97 percent efficiency at a cost comparable to state of the art PFC converters employing conventional less efficient boost topology. This new control method could reduce energy consumption by computers and other electronic devices and systems and enable new energy efficient technologies such as solid state lighting and variable speed motor drives for home appliances. The efficiency of current PFC converters was believed to have reached its limit at 93 to 94 percent when operated with full load and under nominal line conditions. By switching from conventional boost single phase PFC converters to dual boost topology, the researchers believed PFCs could realize a three to four percentage point efficiency increase through the elimination of one semiconductor device. Cost savings could also be achieved by reducing cable power loss through an increase in the input power factor. The new topology with an input power factor >0.999 outperformed conventional diode rectifiers with typical input power factors on the order of 0.7, resulting in additional savings of 2 to 4 W.

Implementation of the proposed technology could result in efficiency increases and cost savings in several technology sectors. Incorporation of dual boost topology could make significant strides toward achievement of the goal of the 80 Plus program to improve overall efficiency of multi-output power supplies used in information technology to 80 percent or higher. Although conventional boost PFC converters may exhibit efficiencies as high as 94 percent, once combined with the efficiency of downstream DC-DC converters, overall efficiency of a typical computer power supply ranges from low 70 percent to mid 80 percent. The additional efficiency gain by the proposed technology could ensure greater compliance with 80 Plus program goals. Use of the proposed technology could also allow for a significant power factor increase over conventional diode rectifiers in variable speed drive and solid state lighting applications, leading to a much larger energy savings potential. The researchers estimated that incorporation of the proposed technology into plug load devices such as computers, monitors, printers, copiers, cordless and cellular phones, battery chargers, and other audio/video equipment could lead to a yearly energy savings of 648 billion watt-hours in California.

Keywords: Power supplies, AC-DC converters, power factor correction, harmonic distortion, dual boost converter, energy efficiency, PFC control

2.14.2 Introduction

Single phase AC-DC converters (rectifiers) are a key component in power supply devices for a wide range of plug-in consumer electronics, industrial controls, solid state lighting, and variable speed motor drives. Conventional uncontrolled diode rectifiers exhibit high input current

distortions, on the order of 50—80 percent, and low input power factor, on the order of 0.7.[50,51] Single boost power factor correction (PFC) converters using the topology shown in Figure 17 overcome these problems and have a near unity power factor but appear to have reached maximum efficiency of 93—94 percent when operated with full load and under nominal line conditions. Recent advances in PFC converter technology have resulted in a new dual boost topology (Figure 18) that has the potential to achieve much higher efficiency than is possible with single boost topology.

The researchers proposed to incorporate the dual boost topology into a PFC converter. They were able to identify areas during research that enabled them to simplify the approach originally proposed. To implement the dual boost topology, the researchers originally proposed a control method using switch current as the feedback signal. This required sensing of either both switch currents or one switch current in conjunction with additional circuitry to reconstruct the current of the other switch. As research progressed, they identified a simplified version of the control method that required sensing of only the DC rail current. They also proposed a prototype to include a mixed signal control board which required both hardware and software development. Research findings allowed them to replace this more complex component with a simplified analog pulse width modulation (PWM) based multiplier. This reduced costs and eliminated the need for software development.

Although conventional boost PFC converters may exhibit efficiencies as high as 94 percent, when combined with the efficiency of downstream DC-DC converters, overall efficiency of a typical computer power supply ranges from low 70 percent to mid 80 percent. By switching from boost single phase PFC converters to a dual boost topology, a PFC can realize a 3—4 percentage point efficiency increase through the elimination of one semiconductor device. The efficiency gain by the proposed technology could ensure greater compliance with 80 Plus program goals. The 80 Plus program[52] is an electric utility funded incentive program which seeks to integrate more energy efficient power supplies in the information technology sector. Use of the proposed technology would also allow for a significant power factor increase over conventional diode rectifiers in variable speed drive and solid state lighting applications, leading to a much larger energy savings potential. The researchers estimated that replacement of conventional uncontrolled rectifiers with the proposed technology into plug load devices

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50 Mohan, M. et al., Power Electronics: Converters, Applications, and Design, John Wiley & Sons, Inc., 3rd Edition, 2003.

51 Fortenbery, B. and Koomey. J.G., "Assessment of the impacts of power factor correction in computer power supplies on commercial building line losses," Report prepared for the California Energy Commission, March 2006.

52 ECOS, 2009. 80 Plus Energy-Efficient Technology Solutions. http://www.80plus.org/

such as computers, monitors, printers, copiers, cordless and cellular phones, battery chargers, and other audio/video equipment could lead to yearly energy savings of 288 billion watt-hours in California. Cost savings could also be achieved by reducing cable power loss through an increase in the input power factor. The new topology with an input power factor <0.999 outperforms conventional diode rectifiers with typical input power factors on the order of 0.7, resulting in additional savings of 2 to 4 watts, depending on the length of the cable. This translates to an additional 360 billion watt-hour savings annually in California.

The researchers achieved all project objectives using the dual boost topology and plan to pursue commercialization of the proposed technology. They measured the efficiency of the dual boost PFC converter as 97 percent for operation at less than 70 kHz switching frequency with a 500 W full load. The input power factor was 0.999 under 60 Hz/110 V input and a full load. For prototyping purposes, they performed the research using a printed circuit board. To provide for the miniaturization necessary for use in solid state and other applications, the technology would need to be implemented using an integrated circuit (IC) approach. The researchers completed preliminary feasibility studies for developing of the IC, but will require additional funding or partnership to pursue this next step toward commercialization.

Figure 17: Boost Single Phase PFC Converter and Its Control by Conventional Linear Average Current Control Method

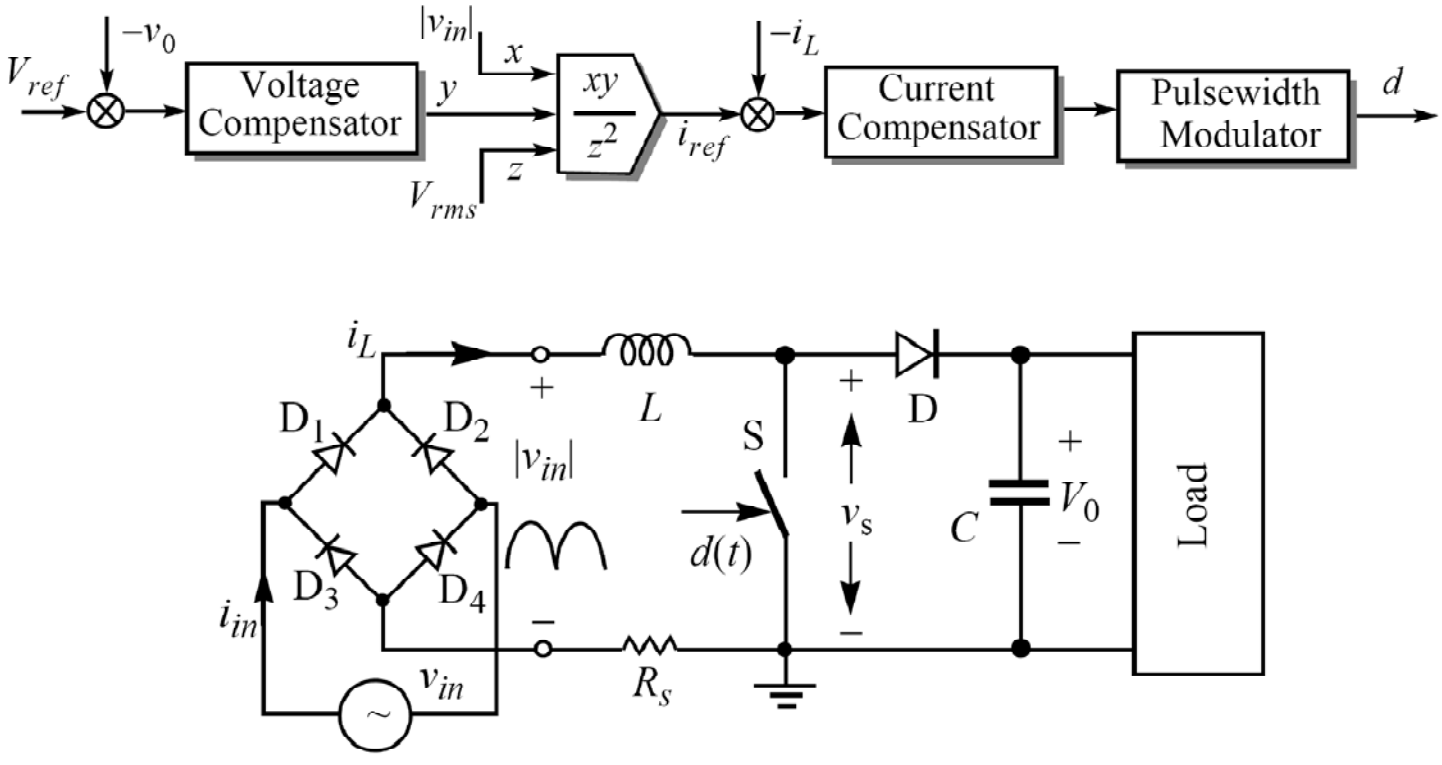
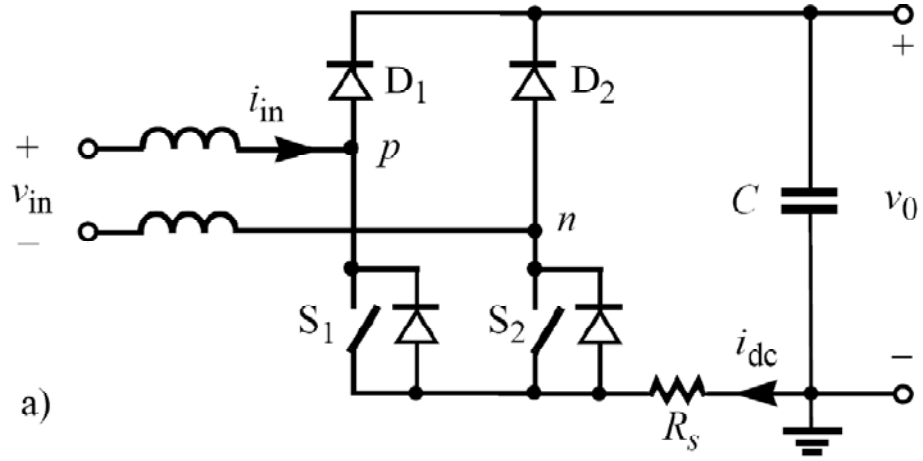


Figure 18: Dual Boost Single Phase PFC Converter Topology



2.14.3 Objective

The goal of this project was to determine the feasibility of applying a new control method to dual boost power factor corrected (PFC) single phase rectifiers to achieve 97 percent efficiency at a cost comparable to PFC converters employing conventional, less efficient boost topology. This new control method could reduce energy consumption by computers and other electronic devices and systems and enable new energy efficient technologies such as solid state lighting and variable speed motor drives for home appliances. The researchers established the following project tasks and objectives:

Design and test current and voltage sensing circuitry for a dual boost PFC converter based on the new control method. Overall control circuitry complexity and cost should not to exceed that required by conventional boost PFC control.

Build and test a low cost, mixed signal control setup for the dual boost PFC converter. Design and test hardware, and develop and test control algorithms. Achieve 0.995 or higher input power factor using a low cost microcontroller with less than 10 kHz sampling frequency.

Develop a 500 W dual boost converter. Optimize power stage design, build a prototype converter, and test prototype operation with DC inputs. Achieve 97 percent efficiency when operated with 200 V DC input voltage.

Test the dual boost converter.Test combined operation of new PFC control with dual boost power stage, and evaluate performance (efficiency, input power factor, harmonics) under different line and load conditions. Demonstrate lower than 5 percent input current total harmonic distortion (THD), higher than 0.995 power factor, and 97 percent efficiency under nominal input conditions and full load.

Input EMI analysis and EMI filter design optimization. Comply with regulatory EMI requirements.

Conduct feasibility and cost analysis of mixed signal control IC for the proposed control scheme. Overall control cost is not to exceed conventional analog control for boost PFC.

2.14.4 Outcomes

1. To implement the dual boost topology, the researchers originally proposed a control method that used switch current as the feedback signal, requiring sensing of either both switch currents or one switch current in conjunction with an additional circuitry to reconstruct the current of the other switch. As research progressed, they identified a simplified version of the control method that required only sensing of the DC rail current. This modification significantly reduced the sensing circuit design effort needed to complete Objective 1. The researchers also proposed the prototype include a mixed signal control board, which required both hardware and software development. Research findings allowed this more complex component to be replaced with a simplified analog pulse width modulation (PWM) based multiplier. This reduced costs and eliminated the need for software development as part of Objective 2. The researchers tested the voltage sensing circuit independent of the PFC control functions.

2. The researchers designed, built, tested, and successfully operated a printed circuit board implementation of the control method with the dual boost PFC converter power stage. They measured the input power factor as part of Objective 4. Control algorithm development was not necessary due to replacement of the proposed mixed signal control board with an analog multiplier circuit.

3. The researchers designed, built, and tested a 500 W dual boost single phase PFC converter power stage. They optimized components, including diodes, switches, inductors, capacitors, and gate drivers, to maximize efficiency and minimize cost. They tested the converter under varying power levels, switching frequency, and gate resistance conditions. Test results demonstrated 97 percent efficiency could be achieved at full power, with 70 kHz switching frequency, and 5 ohms gate resistance.

4. The researchers integrated the sensing circuits, power stage, and control circuit components and tested them to evaluate the performance of the overall dual boost single phase PFC converter. They tested performance of the converter under various line and load conditions, including line inputs of 60 Hz/110 V, 400 Hz, and 800 Hz, and loads ranging from 20 to 100 percent of the rated power. Under 60 Hz/110 V and full power, the total harmonic distortion measured 3.71 percent and the input power factor was 0.999. Higher frequency tests, performed to simulate an airborne power environment, resulted in total harmonic distortion of 2.61 percent. The researchers did not report input power factor at this frequency.

5. Researchers developed differential mode and common mode EMI filters and optimized them to minimize size and losses. Addition of the optimized filter to the converter brought noise levels to within EMI limits defined in EN 55022 Class B at all frequencies.

6. The researchers used a functional block definition along with multipliers to account for interconnects and I/O pads to estimate the chip area required for a dual boost PFC IC.

They estimated the chip area to be less than 0.2 mm^2, excluding I/O pads. Researchers did not provide estimated costs. Neither did they compare cost or chip area for currently used single boost PFC ICs.

2.14.5 Conclusions

1. Researchers met the objective to prototype, test, and optimize the sensing circuit. Analyses confirmed the functionality and superior control performance of the control method. The sensing signal proved to be accurate.
2. Researchers met the objective to build and to test a low cost mixed signal control setup for the dual boost PFC converter.
3. The researchers met the goal of 97 percent efficiency for the dual boost converter.
4. The researchers exceeded the performance goals for the converter in both total harmonic distortion and input power factor.
5. The researchers met the objective to achieve compliance with regulatory EMI requirements at all frequencies. Prior to addition of the filter, the converter was out of compliance at all frequencies.
6. Although the researchers did not meet the objective as stated, they provided a rough estimate of the chip area required to translate the proposed technology into an IC. For this technology to be viable as a replacement of existing PFC control ICs, it must be comparable or lower in terms of size and cost. The researchers stated the anticipated 0.2 mm^2 IC "is an acceptable design for a low cost IC for large volume commercial applications," but gave no analytical basis for this opinion.

2.14.6 Recommendations

The researchers set aggressive performance goals for the dual boost PFC and were successful in meeting them. A more thorough feasibility study (Objective 6) and cost analysis are the logical next steps toward commercialization of the proposed technology. This technology appears to allow for a significant improvement in efficiency of PFC converters. This improvement will help meet efficiency goals as well as reduce costs.

As part of continued development of this technology, the Program Administrator recommends the following tasks be completed:

1. Refine the feasibility study to include comparative costs and sizes between dual boost PFCs and current single boost PFCs.
2. Seek legal advice and pursue protection of intellectual property prior to submitting publications and disseminating trade secrets.
3. Identify potential industry partners for development of the IC.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the

Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.14.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

1 Reduced environmental impacts of the California electricity supply, transmission, or distribution system

2 Increased public safety of the California electricity system

3 Increased reliability of the California electricity system

4 Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. A 2006 study estimated that 3—4 percent of all U.S. electricity is consumed in the power conversion process due to inefficient power supplies with low power factors.[53] Improvement of the input power factor through the use of PFC converters could dramatically reduce electricity loss through power conversion and also through power losses within the power cable. The efficiency gains through adoption of PFC converters could result in a yearly savings of 2366 billion watt-hours in the U.S. (288 billion watt-hours in California). The researchers stated the proposed technology further increases the efficiency of currently available single boost PFCs by 3—4 percentage points, resulting in additional potential savings of approximately 3000 billion watt-hours in the U.S. (360 billion watt-hours in California). They did not give a market penetration assumption for this estimate, but suggested complete replacement of uncontrolled diode rectifiers. Other efficiency benefits might be gained through improvements in device power factor using this technology in solid state lighting and variable speed motor drive applications.

2.14.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

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53 Fortenbery, B. and Koomey. J.G., "Assessment of the impacts of power factor correction in computer power supplies on commercial building line losses." Report prepared for the California Energy Commission, March 2006.

2.14.8.1 Marketing/Connection to the Market

The researchers have not yet performed market research and analysis. The primary focus of the researchers is within the information technology sector for plug-in devices, but the proposed technology appears to have much wider potential applicability. Marketing of this technology is likely to be targeted to the commercial sector for inclusion in products which are sold to consumers seeking certification of compliance with energy efficiency standards such as 80 Plus or Energy Star.

2.14.8.2 Engineering/Technical

The researchers plan to continue product development by translating the technology from a printed circuit board to an integrated circuit.

2.14.8.3 Legal/Contractual

The researchers have not yet filed for patent protection of the technology. Research findings were presented on February 19, 2009, at the IEEE Applied Power Electronics Conference and Exposition in a paper entitled *Dual-boost PFC Converter Control without Input Current Sensing*. Although this publication was not available for review, it likely will impact the patentability of the proposed technology.

2.14.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

Because of technology immaturity, the researchers have not developed these plans.

2.14.8.5 Production Readiness/Commercialization

The proposed technology will not be ready for commercialization until successful implementation of the technology in an IC. The researchers require additional funding or industry partnership to accomplish this objective.

2.15 Feasibility Study of a Symmetrical Flexible Turbine Blade for Wind Energy Conversion

Awardee: San Diego State University

Principal Investigator: Asfaw Beyene

2.15.1 Abstract

In this project researchers investigated the feasibility of improving turbine performance using turbine blades made of rubber (e.g., RU 455) that would change shape under differing wind conditions. The intent was to have the wind change the shape of the blade in ways that optimized the blades' aerodynamic properties under that specific wind speed and thus improving overall efficiency.

Researchers analyzed a two-dimensional elastic airfoil with a hybrid model comprised of X-Foil and Matlab PDE toolbox. The researchers constructed a flexible blade and tested it in a wind tunnel and in the field. They concluded that aeroelastic effects can improve lift as well as the lift over drag ratio at off-design wind conditions. The airfoil deformation decreased linearly with airfoil blade thickness. The thickness was found to be less critical for a flexible blade than for a rigid blade. The researchers concluded that airfoil geometry predictably changed under wind

load has large impact on the lift and drag of the blade and that the bend can be optimized to improve wind turbine performance.

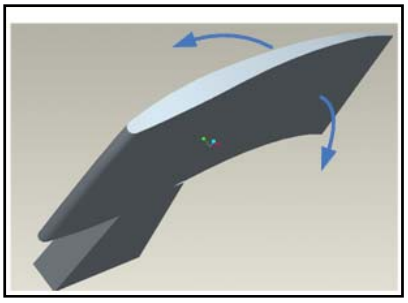
Keywords: Wind energy, turbine, flexible, adaptive, morphing

2.15.2 Introduction

Wind energy conversion varies greatly with wind speed. The power output changes with the cube of wind speed, so even minor changes in wind speed have significant impact on power output. Once at rest, the turbines require a high initial momentum to start. In inherently variable wind conditions, off-design or part load poses serious challenges in wind energy turbine blade design and negatively influences grid integration. Engineers have suggested improving wind turbine performance by modifying, in real time, the aerodynamic properties of turbine blades.

In this project researchers investigated the feasibility of improving turbine performance using turbine blades made of rubber (e.g., RU 455) that would change shape under differing wind conditions. The intent was to have the wind change the shape of the blade in ways that optimized the blades' aerodynamic properties under that specific wind speed and thus improving overall efficiency. Figure 19 illustrates the concept, with the curved arrows showing deformation axis that allows differing leading edge and trailing edge geometry.

Figure 19: 3-D Model of the Proposed Symmetrical and Flexible Turbine Blade



2.15.3 Objectives

The goal of this project was to determine the feasibility of improving wind turbine performance under varying wind conditions using flexible, or elastic, wind turbine blades. The researchers established the following project objectives:

1. Establish computer modeling and design methodologies, develop velocity triangles, and create CAD drawings.
2. Fabricate a sub-scale prototype device.
3. Conduct prototype wind tunnel testing at various loads.
4. Perform manufacturing cost analysis.

5. Perform life cycle cost analysis.

2.15.4 Outcomes

1. The researchers used a hybrid mathematical model to calculate steady and incompressible flow expressed as the two-dimensional Navier-Stokes equations.

2. The researchers constructed a prototype airfoil from a solid material with linear elasticity.

3. The researchers investigated three polymer matrices with varying levels of fill for manufacturing the flexible blade. They concluded RU 455, a semi-transparent rubber urethane, was the most appropriate for this application. Polar comparisons of the flexible and rigid airfoils showed the flexible airfoil delays stalled by two to three degrees compared to the rigid airfoil. In field testing, the researchers demonstrated the flexible blade had a higher RPM for a design wind speed, and it was more efficient than a rigid aluminum blade at part load. There was about 25 percent RPM increase of the flexible blade relative to the rigid blade. The RPM was recorded digitally, with reading error of less than a few percent. However, simplification of a complex 3-D flow regime into a 2-D model introduced significant errors, possibly larger than 10 percent. The researchers found inconsistency between field test results and the mathematical model.

4. The researchers assumed the cost of the blade to be within the price range of existing rigid blades. According to them, the small percentage of a blade cost relative to the system cost, i.e., 10 to 15 percent of a turbine system, made the material cost difference within the error of cost estimates. This did not account for any difference in manufacturing costs.

5. The researchers performed a life cycle cost analysis of generic large and small wind turbines but did not perform one on the specific concept described here, nor did they determine any life cycle cost benefits.

2.15.5 Conclusions

The researchers found flexibility of an airfoil enhanced part load wind turbine efficiency and delay stall. This was partially confirmed experimentally and via modeling efforts, although the performance differed between experimental and modeled conditions. The researchers found proper selection of blade composition material was critical to achieve predictable bend and to match predictability to load conditions.

1. This task met the objective.

2. The researchers accomplished this objective.

3. The researchers demonstrated the concept of using flexible blades to improve performance is possible, but much work remains before the concept can be considered feasible. Inconsistency remains between modeled and measured performance.

4. The researchers did not perform a detailed manufacturing cost analysis.

5. The cost effectiveness of this concept remains uncertain. The analysis performed was not specific to the project design.

2.15.6 Recommendations

There are numerous technical issues to resolve. The researchers should investigate torsional strain and potential for flutter of the blades under gusty wind conditions. The researchers should improve the correlation between actual and modeled performance, including modification, if necessary, to the hybrid model used. This improved correlation will be critical to the development of design tools for the flexible blade. The researchers should perform a comparative life cycle analysis with actual cost estimates for the proposed blade composition, including manufacturing costs.

The researchers should evaluate lifetime of the blade material under outdoor and harsh conditions. RU 455, the material of choice, is a two component urethane elastomer typically used in short term mold applications not exposed to weather. The researchers should investigate performance under wind shear conditions to evaluate blade-up versus blade-down performance and response. The researchers should develop performance curves as a design tool. The researchers should undertake testing and design efforts to insure the flexible blade design is not subject to flex cracking and or to blade failure.

2.15.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

1. Reduced environmental impacts of the California electricity supply, transmission, or distribution system
2. Increased public safety of the California electricity system
3. Increased reliability of the California electricity system
4. Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California electricity supply system. A secondary benefit may be reduced costs by virtue of increased energy capture efficiency for wind turbines, but cost effectiveness remains uncertain.

In 2008 California wind energy capacity was 2,517 MW or about 4780 GWh of annual wind energy production. Assuming only 20 percent of this total came from small wind turbines and the rest from large turbines, approximately 956 GWh/yr came from small turbines and 3826 GWh/yr from large turbines. If these numbers double by the year 2020, consistent with state renewable portfolio standards, the total power output result could be 1913 GWh/yr and 7652 GWh/yr for small and large turbines respectively. If 30 percent of the small blades and only 15 percent of the large blades used flexible blades, approximately 1722 GWh/yr of energy could be from the flexible blades. If the turbines replace fossil fuel driven power plants that generate 2.13 pounds of CO_2, the reduction of 258 GWh/yr would result in 275,030 tons/yr of CO_2 reduction.

2.15.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.15.8.1 Marketing/Connection to the Market

The researchers have held preliminary discussions with a wind turbine manufacturer that might lead to commercialization agreements.

2.15.8.2 Engineering/Technical

The researchers plan to seek funding from an interested manufacturer of large turbines, the California Energy Commission, and the U.S. Department of Energy to fund continued engineering and technical work. They plan to build and test a blade for a 100 kW wind turbine.

2.15.8.3 Legal/Contractual

The researchers have applied for a patent.

2.15.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

There is no evidence the researchers have begun to address these plans.

2.15.8.5 Production Readiness/Commercialization

The product is not ready for production, and commercialization plans are premature until technical issues are resolved.

2.16 Fanless Cooling System for Servers and Storage Systems

Awardee: Clustered Systems

Principal Investigator: Phil Hughes

2.16.1 Abstract

Energy for cooling servers in data centers represents a significant portion of their total power requirements. The typical fan based server cooling system is inherently inefficient, resulting in a total power draw of 70—150 percent of the power actually used by the computing server itself.

If a liquid based cooling design were used, energy savings could potentially reduce these figures by 10—30 percent.

The goal of this project was to demonstrate that direct cooling of server enclosures by liquid cooled cold plates could be achieved in a cost effective manner. The researchers proposed to accomplish this by creating a direct thermal conduction path between a cold plate attached to the server enclosure and its major internal heat generating components.

Keywords: Building energy efficiency, data center cooling, fanless server cooling, liquid server cooling, cold plate, refrigerant, chiller, thermal interface material, cooling fans, power

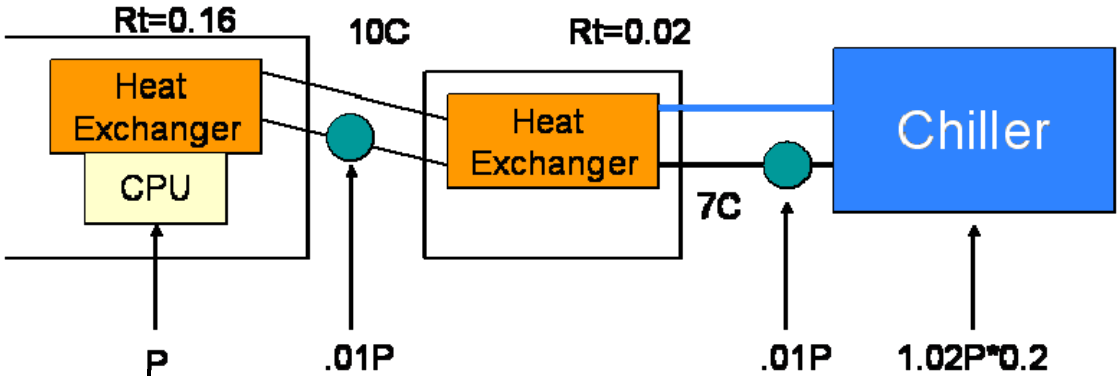
2.16.2 Introduction

Energy for cooling servers in data centers represents a significant portion of their total power requirements. The typical server cooling system relies on air circulation utilizing chillers, computer room air conditioners, rack fans, and internal server fans to maintain required operating temperatures. This approach is inherently inefficient, resulting in a total power draw of 70—150 percent of the power actually used by the server itself.[54]

Applying national estimates for data center consumption of roughly 1.5 percent of total usage suggests that California's data centers consumed an estimated 4500 GWh of electrical energy in 2007 at a cost of $540 million.[55] If a liquid based cooling design were used in lieu of air based, energy savings could potentially reduce these figures by 10–30 percent.

The researchers proposed to demonstrate a cost effective liquid cooling design utilizing heat risers to connect key server components to a server case mounted cold plate (Figure 20). In Figure 20 the symbol "P" is the power used by the server central processing unit (CPU). Expected energy savings result from elimination of fans and heat sinks, as well as energy savings resulting from improved heat transfer.

Figure 20: Proposed Liquid Cooled Server



CPU

2.16.3 Objectives

The goal of this project was to demonstrate that direct cooling of server enclosures by cold plates attached to the case lid rather than conventional fan driven air circulation could be achieved in a cost effective manner. The researchers established the following project objectives:

54 Extracted from Lawrence Berkeley National Laboratory, DC Energy Study, W. Tschudi.

55 Consumption from California Energy Commission 2007 Net System Power Report – Final Adopted Commission Report, publication number CEC-2002008-002-CMF, and assuming a 12c/kwh average retail rate.

Finalize system design and develop mechanical drawings of the system. Create a detailed mechanical design of a low cost, efficient conduction path for components requiring cooling to a cold plate. Create a detailed mechanical design of associated enclosure and supporting structures.

Fabricate one proof of concept device. Device will consist of eight processor server modules attached to eight liquid cooled cold plates. Use the device to demonstrate adequate device cooling using conduction in lieu of fan driven air and heat sinks.

Insert temperature monitors at all critical points. Demonstrate a temperature measurement accuracy of plus/minus 10 percent at critical points.

Finalize test plan. Obtain EISG Program Administrator approval of the test plan.

Conduct proof of concept testing. Demonstrate a central processing unit (CPU) thermal stack resistance of less than 0.4 ^{O}C per watt and maximum temperature rise of other components of less than 30 ^{O}C above cold rail temperature at full computing load. Demonstrate a minimum of 20 percent system power savings compared to standard servers.

Perform manufacturing cost analysis. Confirm that the projected manufacturing cost of $200 per server can be supported.

2.16.4 Outcomes

The researchers completed detailed mechanical designs for the CPU heat risers, an eight position rack together with the cold plate, its engagement mechanism, and server rail supports. Heat risers for other components were simple and did not require detailed design. A qualified HVAC technician fabricated the refrigerant distribution manifolds in place.

The researchers built the device as planned, using seven Dell SC1435 Opteron servers, each with two CPU sockets, and one Supermicro AS-1041M-T2+B server with four CPU sockets and 32 DIMM sockets. Several iterations were required to develop a sufficiently compliant thermal interface material for the server lid using off-the-shelf materials from several manufacturers.

The researchers fitted one Dell server and the Supermicro server with approximately 30 thermocouples each. They monitored all components capable of generating more than two watts.

The researchers did not submit the test plan for approval in the interest of time. Testing included logging temperatures and power consumption before and after conversion of the servers. The researchers took additional measurements to confirm reliability three to four times after the servers and their lids had been removed and replaced in the chassis.

The researchers measured a CPU thermal stack resistance from lid to refrigerant of under 0.2 ^{O}C per watt. Maximum temperature rise of every other component was less than 30 ^{O}C above cold rail temperature at full computing load on the Dell and SuperMicro servers. Removing the fans on each of the Dell and SuperMicro servers reduced power consumption by 10 percent at the wall socket.

Researchers received a production quote of $350 per server for a turnkey system in volume. This quote was based on the prototype design which had not been optimized for manufacturing efficiency and cost.

2.16.5 Conclusions

The project proved feasibility and energy efficiency improvements from cooling data center servers using heat risers to connect key components to a cold plate compared to traditional air based cooling using fans. Report data confirmed a 10 percent reduction in the server power requirement from removal of cooling fans. Although it was not possible to confirm the report's illustration of a total energy savings of 20 percent from the data presented, it was evident that in addition to savings from removal of fans, further savings should be possible using the more efficient liquid heat exchange process compared to traditional air based devices. While the researchers did not confirm the targeted $200/server production cost, the prototype designs used for cost estimates had not been optimized for cost and manufacturing efficiency.

The rack mechanical design process was successful. The researchers noted opportunities to refine the design to reduce costs and improve manufacturing efficiency.

The design proved to be straightforward to construct. Choice of thermal interface material required several iterations and pointed to the need for further refinement of material for production units. The researchers noted the need to accommodate cold plate, case and motherboard flexion, and to ensure mechanical reliability under the load of the cold plate and heat risers.

Temperature monitoring produced satisfactory results. The SuperMicro server allowed direct temperature measurement from placement of thermocouples on the CPU lid. It was not possible to place thermocouples directly on CPU lids for the Dell servers, so the researchers used readings from a thermal diode internal to the CPU. Although this may not have provided an exact measurement of absolute temperatures, it did provide a basis for computing the necessary relative temperature differences across the thermal stack.

Although the researchers did not submit the test plan for approval, it appears that the testing and analysis performed was appropriate to the goals of the project.

The design resulted in a CPU thermal stack resistance from case to refrigerant under 0.2 degrees centigrade per watt. This far exceeded the 0.4 degrees centigrade per watt goal of the project. If this level of performance can be sustained in commercial production, it may not be necessary to cool the water circulating through the servers in many California locations during much of the year, resulting in additional energy savings.It was not possible to confirm estimates of total energy savings of 20 percent using the data and illustrations provided in the report.

The research did not meet its goal of demonstrating that the projected manufacturing cost of $200/server could be supported. However, since the designs used to solicit quotes in this project had not been optimized for manufacturing costs and efficiencies, lower costs could be expected from a more refined design. It is also possible that the total cost of original equipment manufacturers of servers using heat risers in lieu of fans could be lower in production volumes

2.16.6 Recommendations

This project successfully demonstrated the basic concept of direct component to cold plate cooling in a server rack. Further refinement of the design and cost projections, additional prototype testing to demonstrate longer term reliability, and a field demonstration at a commercial site[56] are logical next steps. Development of opportunities to partner with original equipment manufacturers (OEM) rack and server manufacturers should also continue.

There are a number of further engineering refinements which will be important in developing a final commercial product. These include improvements in cost and manufacturability of the thermal interface material for the server lid, a redesign of the overall rack design to reduce manufacturing costs to the $200/server goal, and final specifications for server case and motherboard rigidity and strength under cold plate and heat riser loads.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.16.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

1. Reduced environmental impacts of the California electricity supply, transmission, or distribution system
2. Increased public safety of the California electricity system
3. Increased reliability of the California electricity system
4. Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. The results in this project suggest that if further development results in a successful launch of a commercial product, data center energy consumption could be reduced between 10 and 30 percent and possibly higher if external cooling can be reduced or eliminated. Assuming a 20 percent reduction (the goal of this project) and an estimated 25 percent penetration of this technology, California's estimated 2007 data center energy consumption could be reduced by

56 Clustered Systems has been selected to participate in a comparative testing between various energy savings technologies being conducted by Silicon Valley Leadership Group and Lawrence Berkeley Laboratories. (See http://blogs.sun.com/geekism/resource/images/081008-chilloff2-approach.pdf).

225 GWh, a savings of $27 million. California emission reductions in 2006[57] could be an estimated 2,950,000 metric tons of carbon dioxide, 1,300 metric tons of sulfur dioxide, and 4,500 metric tons of nitrogen oxide.

2.16.8 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.16.8.1 Marketing/Connection to the Market

There are several commercial offerings for direct cooling of at least part of the server, but there does not appear to be any that employ the completely fanless approach anticipated in this project. As existing servers require replacement and data center capacities continue to be expanded to meet increased computing demands, there is strong potential for introduction of a fanless option in a reliable, cost effective package.[58]

2.16.8.2 Engineering/Technical

The Program Administrator has no further information in this area.

2.16.8.3 Legal/Contractual

The researchers indicated that no patents have been received, but one provisional patent application is pending.

2.16.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

Refrigerant selection for this process should be optimized to reduce the potential of releases of gasses with global climate change potential. Quality plans should include testing of multiple units under actual field conditions over an extended time period to demonstrate reliability and serviceability of the design. Given the ongoing concern of IT professionals for reliability, this will be an important driver of market acceptance.

2.16.8.5 Production Readiness/Commercialization

The system is being demonstrated in prototype form to potential financial and manufacturing partners. Once the energy savings, design, cost, and reliability of a more advanced design are confirmed, the system could be ready for commercialization either as a stand alone offering from centered systems or through partnerships with server and rack original equipment manufacturers.

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57 Data from 1990—2006 U.S. Electric Power Industry Estimated Emissions by State (EIA-767 and EIA-906).

58 Using industry data the researchers estimated the total server racks sold in California to be approximately 17,000.

2.17 Residential Sub-Wetbulb Evaporative Chiller System

Awardee: Nexajoule, Inc.

Principal Investigator: Eric E. Jarvis

2.17.1 Abstract

Air conditioning of houses and commercial buildings requires significant energy and high power demands in California. The objective of this project was to validate the feasibility of a sub-wetbulb configuration to utilize evaporative cooling to chill water to below the ambient wetbulb temperature, thus reducing total energy use for air conditioning. The system would use the chilled water to cool a home with a fan and coil system, individual fan convectors, or radiant tubing. Computer simulations showed the sub-wetbulb chiller could satisfy as much as three quarters of the annual cooling load for homes in the Central Valley of California if used in a hybrid configuration with a vapor compression system. The novel sub-wetbulb capability was responsible for over half the predicted power savings. The researchers constructed and tested three different prototype devices. Sub-wetbulb temperatures were achieved under load over a variety of simulated ambient conditions. Preliminary cost estimates for the system put the price at a level that could compete with upper end split system central air conditioners in standalone application, but with improved efficiency.

Keywords: Evaporative cooling, air conditioning, wetbulb, chiller, energy efficiency

2.17.2 Introduction

In 2005 California residents consumed over 9,000 gigawatt hours of electricity for air conditioning.[59] Commercial and industrial heating, ventilation, and air conditioning (HVAC) use a great deal more energy and power. Providing energy efficient and environmentally friendly air conditioning is important to meet California's energy goals.

About 55 percent of California households have either central or window air conditioning.[60] Residential customers currently have the following air conditioning choices:

1. Central air conditioning systems using vapor compression
2. Window/wall units using vapor compression
3. Direct evaporative coolers, also known as swamp coolers
4. Indirect/direct evaporative coolers

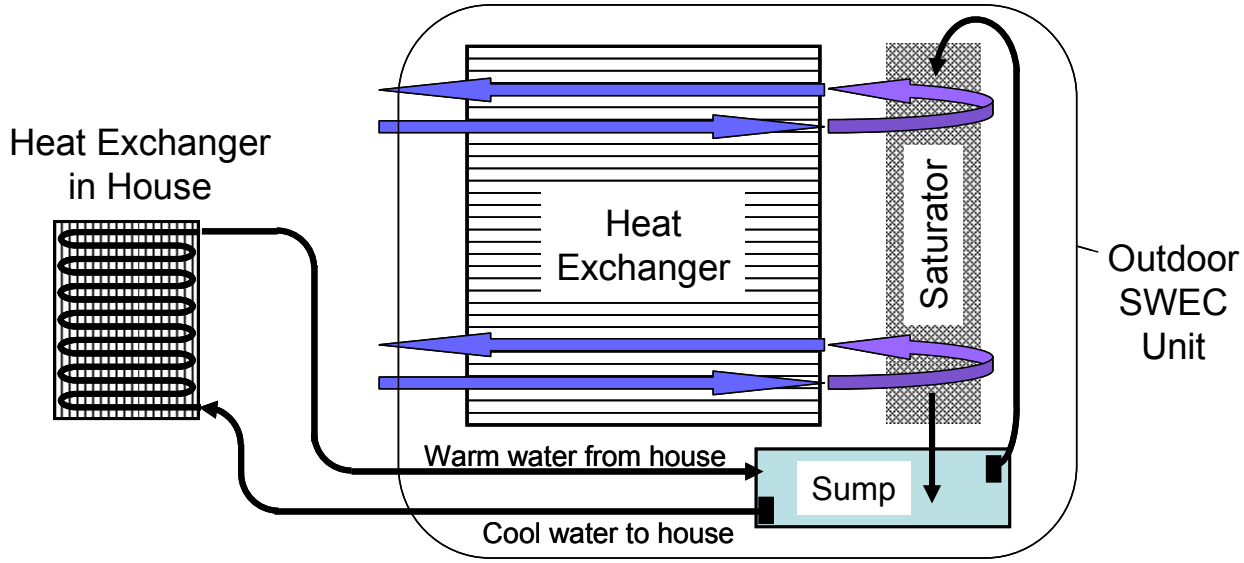
59 http://www.eia.doe.gov/emeu/recs/recs2005/c&e/airconditioning/excel/tableac2.xls.

60 Energy Information Administration. 2005. "2005 Residential Energy Consumption Survey." http://www.eia.doe.gov/emeu/recs/recs2005/c&e/detailed_tables2005c&e.html.

Any of these choices results in high use of energy and high power demands. Some choices provide unsatisfying cooling or high humidity, mold, or consumptive water use.

The researchers proposed a new option for home cooling in dry climates. The proposed concept included a sub-wetbulb evaporative chiller (Figure 21). This unit would be placed at a convenient location outdoors, much like the condenser unit of a split system central air conditioner. The sub-wetbulb chiller produced a stream of chilled water. The chilled water was used to cool the house by circulating it through piping to air-to-water heat exchangers (a fan coil in the forced air system or distributed fan convectors in specific rooms) or through radiant tubing.

Figure 21: General Configuration of the Proposed System Showing the Outdoor Sub- Wetbulb Evaporative Chiller (SWEC) Unit on the Right and the Indoor HeatExchanger on the Left



The proposed innovation in air conditioning would produce lower temperatures than possible with a cooling tower or direct evaporative cooling. Simple evaporative cooling is limited by a property of air known as the wetbulb temperature. The wetbulb is a function of the air temperature and relative humidity. Evaporating water in air, as in a direct evaporative cooler, cools the air to a temperature no lower than the wetbulb temperature and increases the relative humidity, further increasing the wetbulb. However if the air is first cooled without adding humidity, temperatures below the wetbulb (sub-wetbulb) can be achieved. This principle was used in the proposed indirect/direct air coolers. The innovation was to apply this concept to cool a stream of water and to use the cool air leaving the device to pre-cool incoming air.

2.17.3 Objectives

The goal of this project was to prove the feasibility of a sub-wetbulb cooler to provide air chilling in residential applications. The researchers established the following objectives:

1. Model system performance using TRNSYS to predict daily cooling contribution under Sacramento and Bakersfield climatic conditions.
2. Build additional model using Microsoft Excel (objective added after proposal submittal).
3. Set up data logging system with sufficiently accurate measurement of temperature (+/-2° F), relative humidity (+/-5 percent), air and water flow (+/-5 percent), and current/power (+/-5 percent).
4. Conduct prototype testing under various ambient conditions, achieving greater than
2 60 percent sensible heat exchange and greater than 85 percent water saturation of air stream.
5. Collect data over extended operation and demonstrate system with a footprint size of 66 inch wide by 18 inch deep that would provide two tons (24,000 Btu/hr) of cooling under most ambient conditions encountered in the Central Valley of California.
6. Explore manufacturing methods and costs and confirm whether heat exchanger fabrication for less than $300 is realistic, and consistent with full unit manufacturing cost of less than $1,000.
7. Obtain independent testing and validation through the National Renewable Energy Laboratory (NREL), demonstrating two ton cooling capacity and a preliminary Energy Efficiency Ratio (EER) estimate of greater than 20.

2.17.4 Outcomes

1. Using the TRNSYS model, researchers predicted significant energy and cost savings under Sacramento and Bakersfield climatic conditions, with 42 percent to 44 percent of the load handled by the sub-wetbulb chiller. They predicted annual cooling power cost savings of $193 and $282, respectively, relative to conventional EER 10 air conditioning.
2. The researchers used an Excel model to simulate hourly performance in five California cities (Sacramento, Bakersfield, Palm Springs, Los Angeles, and San Jose). They estimated the sub-wetbulb chiller could meet from 69 percent to 80 percent of the cooling load, with annual electricity cost savings ranging from only $13 in Los Angeles to $642 in Palm Springs. The data suggested hybrid systems with a small direct expansion (vapor) unit integrated into the chiller would be necessary to meet California's needs. The proposed sub-wetbulb capability contributed substantially to the efficiency of such systems in the model, in many cases doubling the annual savings. Modeling of radiant cooling systems suggested the sub-wetbulb chiller could meet 98 percent or more of the load in Sacramento and Bakersfield, while using only 20 percent of the energy of traditional air conditioning.
3. The researchers assembled a data logging system with the required accuracy.

4. The researchers constructed and tested three prototype heat exchangers with the goal of improving heat exchanger efficiency. The third prototype achieved greater than 90 percent efficiency.

5. The change of seasons hampered extended operation, but the researchers collected data over a variety of conditions. They demonstrated two tons of cooling only under conditions of low wetbulb ambient temperatures.

6. Preliminary estimates of equipment cost to the consumer were $3,200 for stand alone units and $4,600 for hybrid units. In one test the researchers measured two tons of cooling. Overall loads were below expected, primarily because the temperature drops were less than anticipated. However the researcher achieved sub-wetbulb temperatures and very high efficiency levels. Chiller EER numbers ranged from 25 to 141, while overall system values ranged from 16-33.

7. Independent testing at NREL covered a wide range of temperature and relative humidity. Test results are reported above in Outcome 6.

2.17.5 Conclusions

The researchers confirmed the feasibility of the concept, but significant development work is needed to prove its practicality. Overall, computer modeling demonstrated significant contribution to cooling, at least in hot, dry climates like the Central Valley. Elsewhere, hybrid systems with higher costs would be necessary to provide adequate comfort. Preliminary pricing estimates suggested the concept could compete in some markets but appear limited to new construction, at least initially. Radiant cooling systems emerged as a promising approach to take full advantage of the benefits of the circulating chilled water approach.

The technology is not yet mature or ready for commercialization and considerable development work remains.

2.17.6 Recommendations

The researchers should continue to improve the system performance characteristics to achieve lower output water temperatures with a given physical size of unit, to refine cost, and to develop manufacturing approaches. The researchers should work directly with manufacturers or someone with manufacturing experience to validate cost estimates. Construction trades should be consulted for estimates of installation requirements (e.g., building codes) and costs. More detail on consumptive water use is necessary for broad market acceptance, especially in the Central Valley. After improving system performance the researchers should undertake full scale and complete system testing side by side with vapor compression split package HVAC system meeting expected future Title 24 standards. The researchers should develop installation and maintenance guidelines for technicians and user guides for consumers with special attention to salt buildup on exposed evaporator surfaces and heat exchangers. The researchers should document water circulation pump requirements. They should develop system control schemes and equipment.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.17.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

1. Reduced environmental impacts of the California electricity supply, transmission, or distribution system
2. Increased public safety of the California electricity system
3. Increased reliability of the California electricity system
4. Increased affordability of electricity in California

The primary public benefit of this technology to California ratepayers would be from increased affordability of electricity in California. A secondary benefit would be reduced environmental impacts of the California electricity supply from reduced consumption of electricity. The primary use would be in new home construction, given the need for chilled water interconnections. The new home construction market is currently in a significant downturn, experiencing a 60 percent reduction in 2008 from prior years, and it is unclear when new home construction may resume. However once new construction begins, if rapid growth occurs in the Central Valley, as much as 1,500 gigawatt hours might be saved annually after a period of perhaps 10 years if all new construction used this concept. This is the equivalent of a 200 MW power plant. Individual customers might save $200 to $600 per year on their electric bill, depending on where they live in California, compared to using an air conditioner with an EER of 10.

2.17.8 Overall Technology Transition Assessment

As the basis for this assessment the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.17.8.1 Marketing/Connection to the Market

The researchers had not developed market connections by the end of the project. They expressed interest in assistance in market assessment, particularly in California, and development of the business case surrounding the technology.

2.17.8.2 Engineering/Technical

The researchers plan to continue the technology development. They require additional funding.

2.17.8.3 Legal/Contractual

The researchers applied for a patent under Patent Application 2007/0151278 A.

2.17.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

All of these plans must be addressed as part of the commercialization process. There are no known safety risks associated with the technology concept. The increased use of water for cooling of residences is of concern in California's current and anticipated future water shortage conditions.

2.17.8.5 Production Readiness/Commercialization

The researchers were considering partnering with an existing HVAC manufacturer. They had contacted the Boulder Innovation Center to begin the commercialization process and to make appropriate contacts

2.18 Residential Utility Monitoring System Hardware Development

Awardee: Desert Research Institute

Principal Investigator: Dr. Hampden Kuhns

2.18.1 Abstract

The goal of this project was to build and test a low cost non-intrusive appliance load monitoring (NIALM) system that attributes residential consumption of gas and electricity to specific appliances. Most load monitoring devices presently available to residential consumers monitor whole house consumption rather than that attributed to specific appliances. Although devices have been developed that can disaggregate the loads to appliance-level activity, they are cost prohibitive for the residential consumer.

The researchers sought to extend the current technology to provide a web based utility consumption monitoring system that attributes electric and natural gas costs to specific appliances with a target retail price below $500. The researchers were successful in building and testing a prototype monitoring system (Utility Accountant) to capture utility consumption data, but were unable effectively to reduce and disaggregate the data or to provide output in a web based environment. Their work sought to extend the NIALM algorithms to identify specific loads and activities with individual appliances using a library of unique consumption signatures produced by each activity and appliance. The researchers were able to visually identify consumption activities using rudimentary power time series data, but research did not progress sufficiently to allow application of the NIALM algorithms to provide disaggregation. Problems related to development of a web based output led the researchers to modify their objectives. The new objectives included assembling a data base of appliance signatures and collecting user data for one month. As a result of the setbacks, the researchers collected consumption data for the test residence for a period of one month to allow for further research and development of the disaggregation algorithm and end-user interface.

Keywords: Non-intrusive load monitoring (NIALM), energy efficiency, electricity, natural gas, home energy display

2.18.2 Introduction

Residential and commercial sectors account for 22 and 19 percent of the total energy consumed in the U.S., respectively.[61] Monthly utility bills aggregate energy consumption to consumers over the billing period, often providing usage data a month or more after consumption has occurred. The premise of this project was that this delay in feedback and lack of attribution of consumption to particular appliances or activities prevents consumers from making informed decisions to improve energy efficiency or to modify consumption behaviors.

There are now several devices available to provide real-time feedback on total energy consumption, all retailing for $200 or less. In a study using one such monitor, participants were able to reduce their energy usage between 7 and 10 percent.[62] However such devices are limited in their ability to affect more significant savings as they do not provide users with detailed consumption information on specific appliances. Devices that attribute consumption to specific appliances are priced between $2000 and $7200. These are marketed primarily to commercial and industrial facilities due to their prohibitive cost for residential consumers.

Non-intrusive appliance load monitoring (NIALM) was developed to reduce the cost and effort necessary to attribute energy consumption to specific appliances. Appliances can be uniquely identified by their power load signature. Those appliances that have two states (on or off) are significantly less challenging to identify than those multi-state appliances such as dishwashers and washing machines, which have multiple power load signatures. The use of NIALM requires development of an appliance signature library which can be used to disaggregate the total power consumption to appliance level consumption.

The researchers sought to incorporate the NIALM algorithm into an appliance level load monitoring device, referred to as the Utility Accountant. To make such a device feasible for residential consumers, the researchers set a target retail price of $500. Significant reduction in cost over currently available appliance level load monitors is possible due to recent advances in embedded computing and networking leading to component cost reductions and the availability of the internet to facilitate cost effective information delivery.

The researchers developed and tested two prototype Utility Accountants for a one month period in October 2008. Hardware components for the Utility Accountant include the central data processing, logging, and communications (CDPLC) module shown in Figure 22 and sensors to monitor both electrical and gas usage. The component costs for the prototype totaled $108.14, almost twice the target cost of $62. Data collected by the CDPLC was transferred to a

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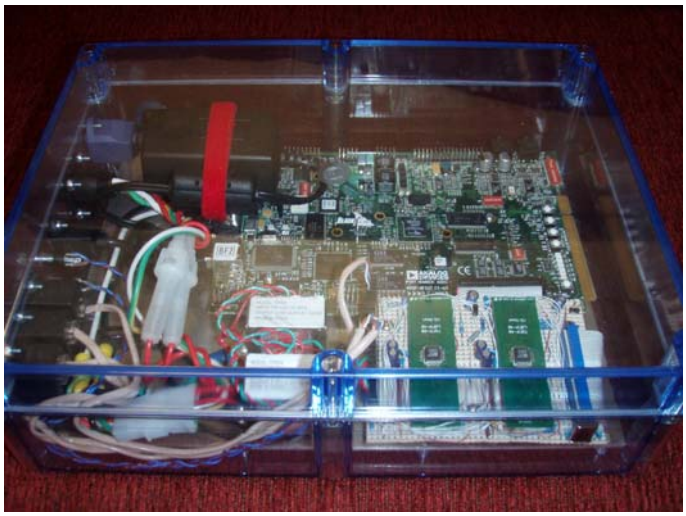
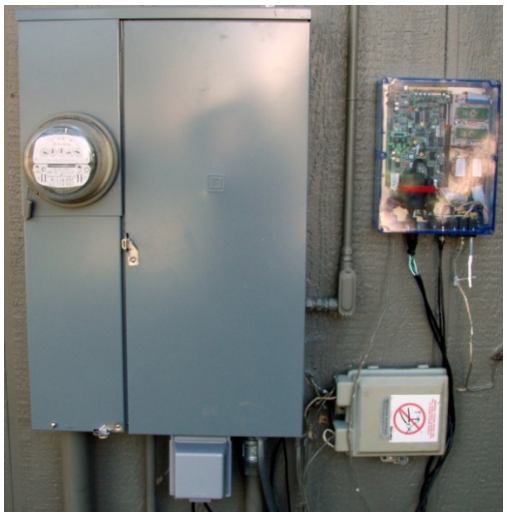
61 "Households, Buildings, Industry & Vehicles End-Use Energy Consumption Data and Analysis, Energy Consumption by Sector, Selected Years, 1949-2008." US EIA (2008). http://www.eia.doe.gov/emeu/aer/pdf/pages/sec2_6.pdf

62 D. Mountain, "The Impact of Real-Time Feedback on Residential Electricity Consumption: The Hydro One Pilot," Mountain Economic Consulting and Associates, Inc. (Ontario, Canada, 2006).

data logging computer for application of the NIALM algorithm to disaggregate loads and present the data to end users. The researchers were successful in prototyping the Utility Accountant and collecting data, but they encountered difficulty in disaggregating the consumption to the appliance level and presenting the output in a web based interface. Had they been successful, studies in Japan using disaggregated consumption data suggest that residential consumers could reduce electrical energy consumption by 18 percent and natural gas consumption by seven percent.[63,64,65] This would be a yearly savings of approximately $195 for the average residence and $234 million for the State of California, assuming a 10 percent market penetration.

Figure 22: Image of DevelopmentPprototype CDPLC Module (left) and System Installed at Residence for Month Long Testing (right)





2.18.3 Objectives

The goal of this project was to build and test a low cost NIALM system that attributes the residential consumption of gas and electricity to specific appliances. This system is referred to as the Utility Accountant. The researchers established the following project tasks and objectives:

63 T. Ueno, "Effectiveness of Energy Consumption Information System for Residential Houses-Effectiveness for Energy Consumption of Whole House, Energy and Resources," 26, 2, pp.139-145. (2005).

64 T. Ueno, F. Sano, O. Saeki, and K. Tsuji, "Effectiveness of an energy-consumption information system on energy savings in residential houses based on monitored data," *Applied Energy*, 83, pp.166-183. (2006).

65 T. Ueno, R. Inada, O. Saeki, and K. Tsuji, "Effectiveness of and energy consumption information system for residential buildings," *Applied Energy*, 83, pp. 868-883. (2006).

1. Design and assemble a CDPLC module. Demonstrate that the Utility Accountant is capable of assigning greater than 95 percent of natural gas and greater than 95 pe rcent of electrical power consumption to specific appliances. Target unit materials cost is $55 (quantity: 1000 units).
2. Design and assemble a voltage and current sensor module. Demonstrate that the Hall Effect sensors correlate with current transducer measurements with an $R^2 > 0.95$ over the AC current range of 0 to 75 amperes (RMS). Target unit materials cost is $5 (quantity 1000 units).
3. Design and assemble optical gas meter sensor module. Demonstrate that the optical gas meter sensor is accurate to within one percent of measured gas consumption on meter over a period of one month. Target unit materials cost is $2 (quantity 1000 units).
4. Design and assemble a Power Line Interface (PLI) module. Demonstrate that an end user can access data stored on the CDPLC module using a web browser. Target unit materials cost is $18 (quantity: 1000 units).
5. Design and program data software for Digital Signal Processor (DSP) and user interface. Demonstrate that the web interface can display time series of appliance loads over the period of one month, total cost per month for each appliance, and heating (and cooling) costs of the building with units of dollars per heating (and cooling) degree day.

During system development and testing, the researchers encountered technical difficulties that required them to revise Objectives 4 and 5 and to add Objective 6 to allow for future research. The revised and added objectives are as follows:

1. Assemble a database of viable physical communication layers for the Utility Accountant, costs to implement, and summarize known issues such as interference and data security for each.
2. Demonstrate that the load disaggregation program can display time series of appliance loads over the period of one month, the total cost per month for each appliance, and the heating (and cooling) costs of the building in units of dollars per heating (and cooling) degree day.
3. Collect one month of raw data for NIALM testing and development.

2.18.4 Outcomes

The researchers constructed two identical prototype Utility Accountants for field testing. They were unable to apply the NIALM algorithm to the consumption data to assign power consumption to specific appliances. They estimated the cost of components of the CDLPC module to be $59.01 in quantities of 1000, slightly above the target of $55.

The voltage sensor consisted of an Analog to Digital Converter (ADC) separated from the Utility Accountant by a transformer connected to each of the two input voltage mains to step the voltage down from about 170 volts to about 4 volts and a secondary voltage divider to reduce the voltage to about 3.3 volts, a voltage level readable by the ADC. The researchers

tested two separate current sensors, Hall Effect sensors and current transformers. They conducted tests using a range of currents from 0 to 18 amperes. Both had a high correlation to the reference current measured in the lab with $R^2 > 0.9997$. The researchers estimated the cost of the components of the voltage and current sensors to be $39.12 in quantities of 1000, well above the target of $5.

The gas flow measurement from the optical gas meter sensor was 8 percent lower than the gas flow measurement reported by the utility gas meter during the one month sampling period. The optical gas meter measurement was 6 percent lower for periods uninterrupted by precipitation. A programming error resulted in a lower than expected voltage to the sensor which may have caused the sensor to miscount the correct number of needle passes on the meter. The researchers also noted an irregularity in the operation of the gas meter dial that caused it to hesitate every fourth rotation. Precipitation further hindered accurate measurements by obscuring the optical path. The researchers require additional research to investigate the source and resolution for the negative bias in the optical gas meter sensor readings. To compensate for this bias until it could be properly diagnosed, the readings were adjusted upward by 6 percent, resulting in an overall precision of 1.7 percent for three time periods, excluding those where precipitation occurred. The researchers estimated the cost of components of the optical gas sensor to be $1.01 in quantities of 1000, below the target of $2.

REVISED OBJECTIVE. The researchers evaluated Homeplug, 802.11 wireless, direct Ethernet cable, USB, and Zigbee communications options. They concluded Zigbee and 802.11 wireless were viable protocols for the Utility Accountant.

REVISED OBJECTIVE. The researchers presented time series data for the 34 day period, from which power usage events could be visually identified. However the NIALM algorithm was not developed sufficiently to disaggregate the events, nor was the interface developed sufficiently to display them. The researchers developed a client-server application in lieu of the web based interface. They isolated the signatures of three appliances from a power time series. Further research is needed to match these signatures with real-time data. The air conditioner was not run during the test period. Heating costs were calculated based on 10 days of heating.

NEW OBJECTIVE. The researchers collected data for 36.5 days at either a 24 Hz or 60 Hz frequency to capture operating properties on eight channels. They encountered problems with "channel hopping" where data was recorded to an incorrect channel, and they also experienced some data loss due to the connection between the Utility Accountant and the data logging computer. Nevertheless, 99.5 percent of the data collected was free of collection error.

2.18.5 Conclusions

The researchers met neither the cost nor performance objective for the Utility Accountant. The estimated cost of the CDLPC module was only slightly higher than the target of $55, but the total of all components comprising the Utility Accountant was estimated to be $108.14, significantly higher than the original target price of $62. The failure to meet the performance objective to assign consumption to specific appliances was crucial to the overall goal of the research performed. Inability to meet this goal necessarily precluded successful achievement of

original Objectives 4 and 5 as well as revised Objective 5. The researchers recognized this significant deficiency and added Objective 6 to further their work toward achievement of Objective 1.

The researchers met neither the cost nor performance objective for the sensors. Although the correlation to current transducer measurements exceeded the objective of $R^2 > 0.95$, the researchers failed to measure the entire range of 0 to 75 amperes as proposed. The reduction in testing range to 0 to 18 amperes was due to test equipment expense. Given the high correlation measured and the linearity reported, it is likely the performance objective would have been met for the range of 0 to 75 amperes. This task did not set a performance objective for accuracy of electrical consumption measurements. However the researchers did state that the Utility Accountant measured 6.6 percent less energy consumption than the electric meter stated. This discrepancy could have been due to calibration of the Utility Accountant or to a positive bias in the electric meter. By adjusting electric consumption measured by the Utility Accountant upward by 6.6 percent, measurements were within 1.7 percent of those shown on the electric meter. Even with the adjustment, this level of precision is less than the one percent accuracy proposed for the gas meter (Objective 3). The source of the discrepancy and improvement in accuracy merit further study. The cost of the voltage and current sensors was approximately eight times the original target price of $5. Should electric meter advancements allow consumption data to be transmitted wirelessly to the Utility Accountant, this component would not be required.

Although the cost objective for the gas sensor was met, the researchers failed to meet the performance objective to measure gas consumption within 1 percent of the gas meter reading. Similar to the electrical consumption sensor (Objective 2), the gas consumption sensor exhibited a negative bias in measurements. Normalizing corrections for this bias increased the accuracy of the readings to within 1.7 percent of the gas meter reading. The sources of the discrepancy in accuracy merit further study. If gas meter advancements allow consumption data to be transmitted wirelessly to the Utility Accountant, this component would not be required.

The researchers met the objective to discuss protocol alternatives and provide related cost estimates. The original objective, providing end-user access to the Utility Accountant measurements, was far more ambitious than the significantly scaled down revised objective. Although the revised objective was met, it did not include testing of any of the alternatives discussed. The revised objective appears to be merely the starting point for the originally proposed Objective 4, which must be completed to provide a viable product to consumers.

The researchers partially met the objective to demonstrate that a load disaggregation program can display time series of appliance loads over one month, the total cost per month for each appliance, and the heating and cooling costs of the building with units of dollar per heating and cooling degree day. Neither the disaggregation algorithm nor the reporting interface was developed sufficiently to meet the objective. Heating costs were calculated as proposed, but cooling costs were not measured or calculated during the testing period.

The researchers met the objective to collect one month of raw data for testing and development.

2.18.6 Recommendations

Although the researchers were unable to achieve their overall project goal, the technology appears promising. Hardware costs were approximately twice that anticipated, but still well below the target price point of $500. The analysis and reporting modules for the Utility Accountant still require significant development. The researchers have entered into a licensing agreement with IBUCS and are pursuing additional funding for continued development that might be able to offset the expense of the remaining research to maintain the low target price. There is a clear need for a device that can offer consumers real time feedback so they may actively and efficiently participate in energy savings initiatives of the State of California.

As part of continued development of this technology, the Program Administrator recommends the following tasks be completed:

1. Complete the original objectives of this project.
2. Investigate the feasibility of providing a Utility Accountant that users can install without the aid of an electrician.
3. Investigate integration of D-Wave appliance level controls when usage exceeds user determined threshold levels as measured by the Utility Accountant. D-Wave technology is currently available to remotely and automatically control heating/ cooling, as well as any device that can be plugged into an electrical outlet.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.18.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

1. Reduced environmental impacts of the California electricity supply, transmission, or distribution system
2. Increased public safety of the California electricity system
3. Increased reliability of the California electricity system
4. Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. A Utility Accountant could provide users real-time appliance specific consumption information that could allow them to modify usage behavior and replace inefficient appliances.

A Japanese study that provided users with appliance level energy consumption data resulted in reduction of electrical consumption by 18 percent and gas consumption by 9 percent. Assuming these savings can be realized, the average California residence could save $127 per year in electricity and $68 per year in gas. If the unit could be produced and sold for the proposed $500, the payback period is 2.5 years. With a 10 percent market penetration, this translates to a state-wide savings of $234 million.

2.18.8 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.18.8.1 Marketing/Connection to the Market

The researchers have not yet performed market research and analysis. The initial target market is residential homes. However this technology could also be applicable to the small commercial sector.

2.18.8.2 Engineering/Technical

The researchers plan to continue software development, hardware development, and technical trials, and they have identified numerous areas requiring research to meet the original project goal.

2.18.8.3 Legal/Contractual

The researchers have filed for patent protection of this technology.

2.18.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

Because of technology immaturity, these plans have not been developed.

2.18.8.5 Production Readiness/Commercialization

The researchers have entered into an exclusive licensing agreement with Intelligent Building Utility Conservation Systems, LLC and are developing a commercialization plan.

2.19 UV Photodecomposition of Siloxane

Awardee: GC Environmental, Inc.

Principal Investigators: Richard W. Prosser

2.19.1 Abstract

The goal of this project was to develop an economical and robust process to remove siloxane-bearing silica from biogas by evaluating the technical feasibility and environmental implications of a novel photodecomposition technology within the context of biogas treatment. Treatment involved first using UV light to break down the siloxane structure to silica dioxide powder and then removing the precipitate via a downstream filtration process. The researchers tested the UV photodecomposition process by introducing air mixed with linear (L2) and cyclical (D4) siloxane and again using a constructed artificial biogas consisting of methane, carbon dioxide, oxygen, nitrogen, and siloxanes. Initial experimentation showed no detectable breakdown of

D4, therefore subsequent biogas testing excluded D4 as a contaminant. Although linear siloxanes readily decomposed, the UV photodecomposition process did not affect cyclical siloxanes, which are the more predominant contaminant in biogas. Additionally, the technology proved to be cost prohibitive due to the low efficiency of the UV lamps.

Keywords: Siloxane removal, biogas, landfill gas, photodecomposition

2.19.2 Introduction

Biogas collected from sanitary landfills is a potentially valuable fuel for energy production, but it is largely untapped due to contamination with siloxanes. Siloxanes are a family of organic compounds containing alternating silicon and oxygen atoms and methyl groups. They are common constituents in many products including detergents, shampoos, deodorants, and cosmetics. Increased use of siloxanes in recent years has resulted in increased levels of siloxane contamination in biogas. Gary Wheless measured landfill gas siloxane contaminants and found linear (L2 and L3) and cyclical (D3, D4, and D5) siloxanes in concentrations as shown in Table 2.[66] These concentrations exceeded allowable limits imposed by many engine manufacturers, necessitating costly pretreatment prior to use. Consequently only a fraction of the captured biogas is presently used for power generation.

The researchers proposed a biogas treatment process to remove siloxanes through ultraviolet (UV) photodecomposition using a reactor as shown in Figure 23. Experimental results demonstrated 97.72 percent removal of the introduced linear siloxane L2, with the potential for increased removal with longer residence time and greater UV lamp energy. However there was no observable decomposition of the cyclical D4 siloxane introduced.

The researchers determined the proposed technology was cost prohibitive and technically infeasible due to the low UV lamp efficiency of 0.77 percent and the inability to decompose cyclical siloxanes, the more predominant contaminant in biogas. They planned to continue investigating the absorption spectra for D4 siloxanes, photochemical reaction pathways, and more efficient UV sources. Should they be successful in providing a treatment process to reduce siloxanes to an acceptable level, the researchers estimate an additional 118 MW of power could be captured from biogas annually in California.

Table 2: Siloxanes in Landfill/Digester Gas and Maximum Allowable Siloxanes in Landfill Gas

Unit: ppmv as Si			
Site (State/Type)	SC Landfill	VA Landfill	CA Digester

66 Gary D. Wheless,"Siloxane in Landfill and Digester Gas" (California, 2002), 25th Annual Landfill Gas Symposium.

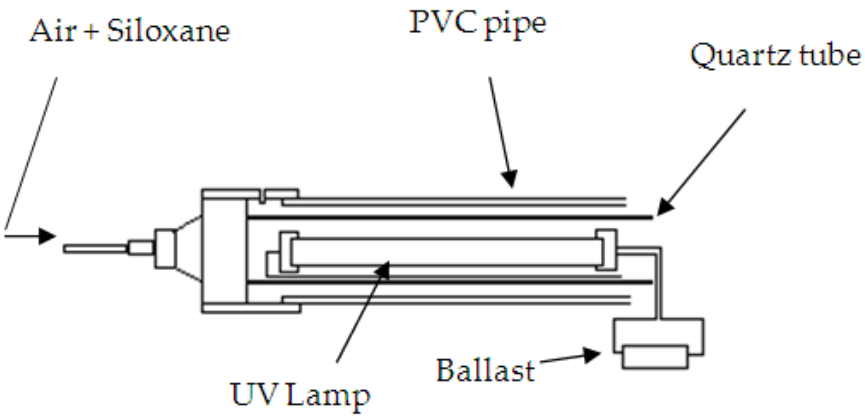
L2 (MW: 162)	0.38	1.18	0.22
L3 (MW: 236)	0.06	0.06	*
D3 (MW: 222)	0.17	0.39	*
D4 (MW: 297)	3.95	5.22	0.79
D5 (MW: 371)	3.46	0.59	11.95
Total Si (ppm)**	7.58	9.47	12.96***
Total Si (mg/M^3)**	9.50	11.86	16.24***

*: Information not available

**: Includes other minor species

***: will be larger if data other siloxane species is available

Figure 23: UV Photodecomposition Reactor



2.19.3 Objectives

The goal of this project was to determine the feasibility and environmental implications of a novel technology involving the in situ photodecomposition/photooxidation of siloxanes from landfill gas and digester gas. The researchers established the following project objectives:

1. Confirm the absorption spectra of siloxane and oxygen.
2. Assess quantitatively the absorption spectra of siloxane and oxygen.
3. Demonstrate the capability of 90 percent photodecomposition reaction yield.
4. Identify the photochemical reaction pathways.
5. Assess quantitatively the effect of controlling parameters.

6. Demonstrate the capability of removing 99.95 percent of the siloxane.
7. Confirm the feasibility of on-site siloxane removal to support energy production.
8. Confirm siloxane emissions of less than 5 ppbv for a 3,500 standard cubit feet per minute (SCFM) project (assuming 100 ppmv Si in the influent gas).
9. Confirm that the photochemical system can remove 44.66 tons of siloxane per year for a 3,500 SCFM project.
10. Confirm the financial viability for a medium size (>500 SCFM) project.

2.19.4 Outcomes

1. The researchers measured the absorption spectra using an Agilent UV Spectrophotometer that had a wavelength range of 190 to 400 nm. A literature review revealed the L2 absorption cross-section at 190 nm is 1×10^{-18} cm^2/molecule. Experimental results at 190 nm indicated a slightly higher absorption cross-section of 2.5×10^{-18} cm^2/molecule for L2 siloxane. The absorption spectra for D4 siloxane could not be determined either through literature review or laboratory experiment. A literature review found the absorption cross-section of oxygen at 190 nm to be $1.3 \times 10^{-20.}$ This value was not confirmed through experiment.
2. The researchers measured the absorption cross-section of L2 siloxane and determined the cross-section of oxygen by literature review.
3. The researchers conducted photodecomposition experiments for an L2 and air mixture with a 0.20 second residence time. The average reaction yield was 90 percent. The researchers tested mixtures containing D4 siloxane using UV lamps with wavelengths of 185 and 120 nm, but there was no measurable photodecomposition. Consequently, experiments performed for the remainder of the objectives omitted D4 siloxanes and included only L2 siloxanes with mixtures of air and derived landfill gas mixtures.
4. Upon completion of the photodecomposition experiment, the researchers collected the reaction byproducts (N_2 + O_2 + siloxane + CH_4 + C_2H_4 + C_2H_6) for analysis. They used a gas chromatograph with a flame ionization detector to analyze for C_2H_4 and C_2H_6 to determine siloxane concentrations through a process of elimination. However the column could not adequately separate the gasses. Consequently the researchers conducted a literature review to determine that C_2H_6 is the primary photodecomposition product.
5. The researchers originally proposed to investigate the effects of residence time, temperature, UV energy level, concentration, and pressure. Because the two UV lamps acquired for experimentation did not vary in UV energy level, this parameter could not be investigated. The only difference between the two lamps was length, corresponding to residence times of 0.20 and 0.71 seconds. The researchers performed three experiments as listed below. They did not address pressure and temperature effects.

Mixture analyzed	Residence time (s)	Average Reaction Yield (percent)
Air + L2 siloxane	0.20	90.00
Air + L2 siloxane	0.71	97.72
Landfill gas + L2 siloxane	0.20	90.50

6. The researchers extrapolated results from Objective 5 and numerically determined that 99.95 percent removal of L2 siloxane was possible with a 2.13 second residence time and 2.02 x 10^5/(cm^2s) photon flux.

7. The researchers evaluated a conceptual reactor including reaction chamber, cooling system, and silica dioxide separation equipment. The model assumed 3,500 SCFM input with 50 ppm L2 siloxane and 96.6 percent siloxane removal efficiency at the outlet. This corresponded to a residence time of 0.5 seconds. The conceptual reactor would consume around 240 kW and would be nominally 30 feet in diameter and 26 feet high, costing approximately $492,000. Including operation and maintenance, the UV system would cost $892,000, compared to $1,050,000 for adsorption and $870,000 for absorption.

8. The researchers confirmed siloxane removal to 5 ppbv (99.99 percent removal). The energy used to accomplish this removal is difficult to determine since the researchers confused energy and power in their final report.

9. For the conceptual 3500 SCFM reactor, the researchers calculated L2 siloxane removal to be approximately 19 tons per year.

10. The researchers modeled a third conceptual reactor assuming 96.6 percent removal of L2 siloxanes with a 500 SCFM input. The conceptual reactor would consume 35 kW. Because of the extremely low (0.77 percent) efficiency of the UV lamp, the researchers determined that a 500 SCFM reactor is not financially viable at this time.

2.19.5 Conclusions

1. The researchers were not successful in confirming or quantitatively assessing the absorption spectra of siloxane and oxygen. Although they found the spectra in a literature review for L2 siloxane and confirmed this through experimentation (with slightly higher results), the inability to identify the D4 spectra presented a significant setback. The researchers suggested this is a primary focus of future research.

2. See Conclusion 1 above.

3. The researchers were not successful in demonstrating a 90 percent photodecomposition reaction yield of the siloxanes tested. Although decomposition of L2 siloxane was within the target objective, D4 siloxane had no measurable decomposition. Failure to meet this objective is perhaps the most significant reason the technology is not feasible in its

current state. Cyclical siloxanes are between 8 and 58 times more prevalent than linear siloxanes in samples analyzed by Wheless. Without the ability to impact the concentration of cyclical siloxanes, the technology will not be able to reduce contaminant concentrations to within maximum allowable limits determined by engine manufacturers. Research toward understanding the absorption spectra for D4 siloxane could lead to modifications of the technology so it could ultimately become viable.

4. Although the researchers were not successful in determining the photochemical reaction pathway through experimentation, a literature review confirmed that C_2H_4 and C_2H_6 are the primary products of the photodecomposition process.

5. The researchers had only limited success in quantitatively assessing the effect of controlling parameters. They determined the effect of residence time by using lamps with residence times of 0.20 to 0.71 seconds, but without additional data points the nature of the relationship could not be established (linear or exponential). Similarly, the researchers assessed concentration effects using only two tests which mixed either air or landfill gas with L2 siloxane. Because the researchers did not vary the concentration of L2 siloxane in these experiments, they could not establish a relationship describing concentration effects of siloxane from experimental data. They did not quantify pressure, temperature, and energy level effects due to limitations of the selected equipment and omission of supporting experimentation.

6. The researchers were not successful in demonstrating the capability of removing 99.95 percent of the siloxanes, including both linear and cyclical siloxanes as originally proposed. They were successful in numerically determining that 99.95 percent of the L2 siloxanes could be removed. However the analysis is questionable due to the significant extrapolation required. The two data points presented in Objective 5 at 0.020 and 0.71 seconds are not sufficient to establish a linear relationship and are an order of magnitude below the extrapolated value of 2.13 seconds, causing concern for error propagation. Figure 8 in the report appears to include laboratory experiments performed at 0.02 and 0.71 seconds residence time, as well as the calculated value at 2.13 seconds, along with three other data points not discussed in the text. The source of the data in this figure was not well described, and because it appears to include both laboratory determined values and extrapolated values, the appropriateness of the curve fit is questionable. Regardless, even if L2 siloxanes were completely removed through the proposed technology, cyclical siloxanes would still be present in their original concentration.

7. The researchers were not successful in confirming the feasibility of on-site siloxane removal to support energy production, including both linear and cyclical siloxanes as originally proposed. It is not reasonable to assume that cyclical siloxanes will not be present. Therefore the technology is not feasible in its present state. In the cost analysis the researchers eliminated absorption as a suitable process due to its inability to reduce siloxane to the requisite concentration. Following this logic, the UV system should similarly be eliminated.

8. The researchers were not successful in confirming siloxane emissions of less than 5 ppbv for a 3,500 SCFM reactor, including both linear and cyclical siloxanes as originally proposed. Rather than including 50 ppm L2 siloxane and 50 ppm D4 siloxane, only L2 was considered in the analysis. Assumptions used for the model were not well supported. For example, the calculated efficiency from Objective 6 was 99.95 percent at 2.13 seconds, lower than that used for the conceptual reactor. Further, the efficiency calculated in Objective 6 is questionable due to lack of experimental support (see Objective 6 above). The calculated reactor size is more than three times larger than that determined for Objective 7 and is likely unfeasible and cost prohibitive.

9. The researchers were not successful in confirming the photochemical system can remove 44.66 tons of siloxane per year for a 3,500 SCFM project. The amount removed by the 96.6 percent efficient plant was approximately 30 percent of the target objective. The objective originally included removal of both cyclical and linear siloxanes, which might have brought the removed quantity much closer to the goal had UV photodecomposition been effective for both types of siloxanes. Although the increased plant efficiency included in the conceptual plant for Objective 8 would have further narrowed the gap between actual and proposed removal quantities, the plant does not appear to be a practical or cost effective solution.

10. The researchers were not successful in confirming the financial viability for a 500 SCFM project. In addition, the researchers estimated the initial cost and operating cost of the larger 3500 SCFM UV reactor over a 10 year period. The UV reactor had an initial cost about 10 percent higher than an absorption reactor. The researchers conceded the process was not financial feasible.

2.19.6 Recommendations

The researchers were unable to demonstrate the feasibility for in situ photodecomposition of siloxanes from landfill and digester gas. Although they had success in treating linear siloxanes, the process resulted in no measurable impact on cyclical siloxanes. The researchers recognized the need for additional research to address this deficiency. Had the process been effective for both species, the technology was still cost prohibitive due to the inefficiency of the UV source. Improvement in UV efficiency is another focus of additional research. Assuming both of these issues can ultimately be addressed and given the relative success in decomposing the linear siloxanes, the technology could prove to be quite valuable. As part of continued development of this technology, the Program Administrator recommends the following tasks be completed:

1. Improve the technology sufficiently to provide for decomposition of cyclical siloxanes.

2. Investigate more efficient UV sources.

3. Determine the conditions under which cyclical siloxanes can be decomposed.

4. Repeat the conceptual plant modeling using improved efficiencies and inclusion of cyclical siloxanes.

5. Address efficiency and cost concerns to prove viability.

6. Perform a detailed life cycle analysis and comparison between the improved UV system and a similar capacity adsorption system.

2.19.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

1. Reduced environmental impacts of the California electricity supply, transmission, or distribution system
2. Increased public safety of the California electricity system
3. Increased reliability of the California electricity system
4. Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. Currently California generates 275 MW of power using landfill gas. The researchers estimated that an additional 188 MW of power could be captured if siloxane contaminants could be reduced in landfill gas. Removal of the siloxanes as a precipitate could also reduce particulate emissions into the atmosphere by approximately 175 tons per year.

2.19.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.19.8.1 Marketing/Connection to the Market

The researchers identified a substantial need for this technology in the industrial sector.

2.19.8.2 Engineering/Technical

The researchers plan to investigate more efficient UV sources for the practical application of this technology. They also plan to determine conditions needed to break D4, D5 bonds. They estimate that additional engineering will take three years.

2.19.8.3 Legal/Contractual

The researchers have performed a patent search and have filed a provisional patent for the technology.

2.19.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

The technology is not yet viable, and thus it is premature for preparation of environmental, safety, risk assessment/quality plans.

2.19.8.5 Production Readiness/Commercialization

Once the technical hurdles have been overcome, the researchers plan to pursue commercialization. While they have not developed commercialization plans yet, they plan to commercialize the product without partners.

2.20 Evaluation of a CO2 Mitigation Option for California Coastal Power Plants

Awardee: University of California, Santa Cruz

Principal Investigators: Greg H. Rau

2.20.1 Abstract

Fossil fuel powered electric generating plants are a major source of greenhouse gas emissions in California. A significant number of these plants are powered by natural gas, are located near the coast, and use once-through seawater for cooling. This project investigated the use of wet mineral carbonate in seawater to scrub CO_2 from a simulated gas effluent of a natural gas powered generating plant. Either coral or limestone aggregate supplied the mineral carbonate. The researchers demonstrated removal of up to 97 percent of CO_2 from an air gas stream that contained 10 percent CO_2 using a meter scale gas-seawater-carbonate flow reactor. They found the amount of CO_2 removal was inversely proportional to the water/gas flow rate. The conversion of absorbed molecular CO_2 to dissolved calcium bicarbonate increased with the amount of carbonate surface area exposed to the seawater stream and with the duration of exposure. Downstream seawater carbon content increased by up to 4.5 times that of ambient seawater. As much as 79 percent of the added carbon was converted and permanently stored primarily as dissolved calcium bicarbonate without carbonate precipitation or further CO_2 degassing. Preliminary testing of marine test species incubated in alkalized seawater over a 35 day period revealed that the process did not adversely affect invertebrate growth and reproduction. The researchers concluded that wet carbonate scrubbing of coastal power plant flue gas could provide a safe, cost effective way of mitigating CO_2 emissions, especially those located near limestone deposits and using once-through pumped seawater for cooling.

Keywords: CO_2, mitigation, power plant, flue gas, carbonate, bicarbonate, limestone, seawater

2.20.2 Introduction

California is the twelfth largest source of climate change or greenhouse gas (GHG) emissions in the world, exceeding most nations.[67] California's electricity consumption accounted for 25 percent of its GHG production in 2004.[68] In 2008 45.75 percent of the state's electricity was produced by burning natural gas, 18.25 percent by burning coal, and 2.1 percent by burning biomass.[69] Of these, only the 2 percent from biomass was carbon neutral,[70] being derived from recent photosynthesis processes, while the 64 percent from natural gas and coal combustion was

67 http://www.climatechange.ca.gov/climate_action_team/reports/2006report/2006-04-03_FINAL_CAT_REPORT_EXECSUMMARY.PDF

68 http://www.arb.ca.gov/cc/factsheets/ghginv.pdf

69 http://www.energyalmanac.ca.gov/electricity/total_system_power.html

70 http://biomass.ucdavis.edu/materials/reports percent20and percent20publications/2006/2006_Biomass_Roadmap. pdf

a net undesired positive carbon contribution to GHG. Since a major goal of PIER research is to reduce the environmental impacts of California's electricity supply, transmission, and distribution system, there is great interest in finding ways to capture and sequester the carbon dioxide produced in electricity generation before it is released into the atmosphere. Much attention has focused on the capture, pressurization, and sequestering of the CO_2 from an effluent stream in geologic formations.[71] With combustion in air, the exhaust is strongly diluted with gaseous nitrogen (N_2) which must first be removed, adding cost to this method of sequestering the CO_2. The world's oceans, however, are also a large resource for long term CO_2 storage.[72] An alternative approach would be to capture unpurified CO_2- containing waste streams from power plants and dissolve the CO_2 in oceans. This method is particularly attractive because many of California's natural gas powered generators are located near the ocean and use seawater for cooling. Accordingly, such an environmentally benign and economical process for storage in oceans would be of great interest.

Given California's present power mix, the potential payoff of an economical carbon sequestration technology would be a large reduction of GHG emissions from electricity generation. In 2008 electrical generation by fossil fuels of natural gas, coal, and biomass accounted for 202,421 GWhrs of the 306,577 GWhrs of total electricity consumption of California.[72] Assuming going forward that all fossil fuel generation both in state and out of state would meet California's allowed GHG standard of 1100 lbs[73] of CO_2 per MWhr of electricity generated (AB 32), this combined generation would release 2.23×10^{11} lbs or 101 MMT (million metric tons) of CO_2 into the atmosphere. Thus a successful sequestration technology could

capture up to 101 MMT of CO_2 release per year, of great benefit to California's efforts to reduce the environmental impact of the state's electricity use.

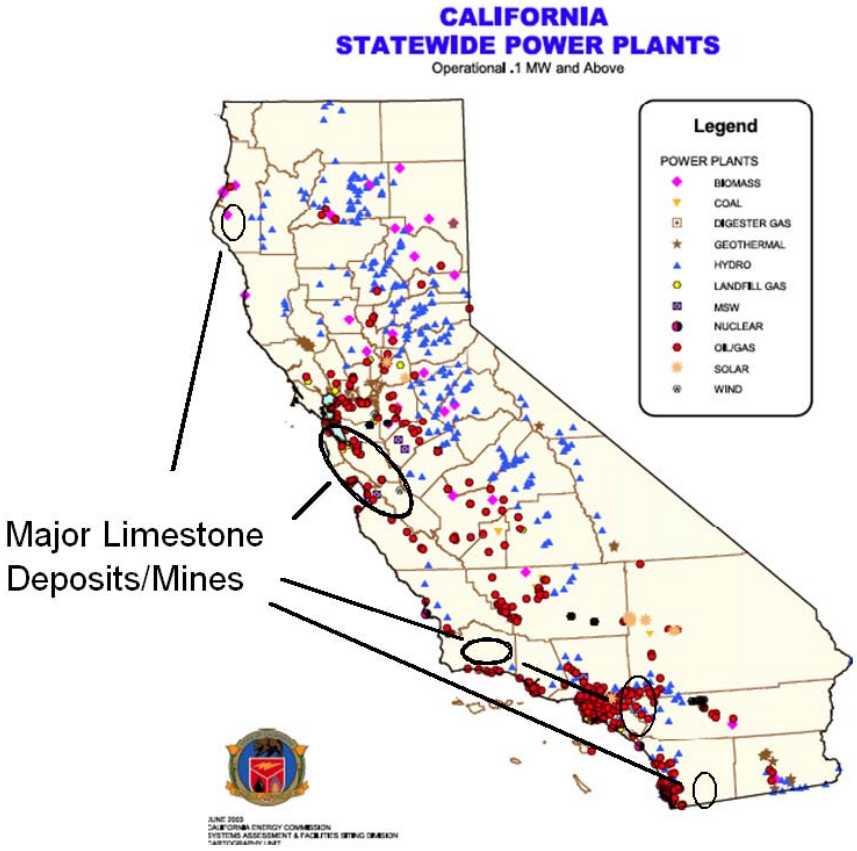
The advancement of science proposed in this project was to investigate the long term storage of carbon dioxide in seawater by wet scrubbing of flue gas with limestone. The initial application targeted was coastal power plants which use once-through plant seawater cooling and are close to limestone deposits. The researchers' identified candidate sites are shown in Figure 24.

71 http://www.netl.doe.gov/technologies/carbon_seq/index.html

72 http://www.sciencemag.org/cgi/content/short/305/5682/367

73 http://www.netl.doe.gov/publications/proceedings/09/CO2/pdfs/NETL percent20OSAP percent20CA percent20GHG percent20analysis percent20(Grol) percent20mar09.pdf

Figure 24: Map of California Power Plants and Locations of Near Coastal Limestone Mines and Deposits



Researchers conducted a feasibility test with a meter scale lab test reactor using the reaction ofcarbon dioxide, water, and limestone (calcium carbonate) to produce dissolved calcium and bicarbonate ions in solution:

$$CO_{2(g)} + H_2O_{(l)} + CaCO_{3(s)} \rightarrow Ca^{2+}_{(aq)} + 2HCO_{3}^{-}{}_{(aq)}.$$

With high CO_2 concentration, the reaction above is driven to the right, leading to carbon dissolved in seawater as a bicarbonate. Once discharged in a low CO_2 environment downstream and exposed to air, this reaction could reverse, leading to degassing of CO_2 and precipitation of limestone. However, in seawater the presence of dissolved mineral and organic material greatly impedes calcium carbonate precipitation. Secondly, the higher density of discharge should sink in the ocean, keeping the majority of the solution from contact with air. The project studied the rate of dissolution of CO_2 as well as the two mentioned back reactions. It also investigated the effect of the dissolved carbon effluent on sea life.

2.20.3 Objectives

The goal of this project was to determine the feasibility of using wet limestone scrubbing of flue gas to reduce CO_2 emissions safely and cost effectively from coastal power plants. The researchers established the following project objectives:

1. Employ or construct and test a computer model of seawater carbon chemistry.
2. Demonstrate that the model accurately predicts seawater carbon chemistry in normal seawater chemistry regimes to within ±5 percent.
3. Conduct lab experiments to test/validate model predictions under elevated carbon conditions relevant to CO_2 sequestration, and measure effects on downstream chemistry and biology. Demonstrate that deviation between predicted and observed seawater chemistry at elevated carbon conditions is within ±5 percent, and carbonate precipitation and organism survival are within ±5 percent of that in experimental controls.
4. Use the preceding models and observations, together with power plant data, to predict feasibility, impacts, optimum designs, and supply/cost curves of large scale application in California. Demonstrate that predicted large scale application would mitigate 25 percent of in state emissions from coastal power plants at a cost ≤$20/ton CO_2 avoided, with minimal downstream impacts.
5. Compare and evaluate cost effectiveness with other CO_2 mitigation options. Demonstrate that at coastal locations wet limestone scrubbing would be less expensive than competing technologies for CO_2 capture/storage.

2.20.4 Outcomes

The researchers employed a widely used ocean chemistry model which predicts equilibrium seawater chemistry under a range of CO_2 and carbonate concentrations. When compared with experimental measurements under the non-equilibrium conditions in the flow reactor, it routinely underestimated pH and overestimated total dissolved carbon and alkalinity.

The first lab reactor of about 0.5 m length removed up to 97 percent of the CO_2 in the incoming gas stream. However researchers found the dissolved carbon was in the form of molecular or hydrated CO_2, which would readily degas when exposed to air. To dissolve carbon as a long lived bicarbonate species, the researchers added a second downstream reactor with much greater limestone surface area. They also investigated longer residence times in the reactor. Air purge tests showed these measures resulted in long lived retention of 47 percent to 79 percent of the dissolved carbon due to bicarbonate formation. Incubation of marine species showed no statistically significant adverse effects due to the dissolved carbon.

The researchers concluded that the small scale of the experiments, the use of simulated rather than real flue gas, and the non-optimized design of the research reactor compromised their ability to forecast large scale application of the approach. Nevertheless they analyzed CO_2 mitigation with large scale application using the experimental parameters. They estimated that

California's coastal gas fired power plants produce about $1.3X10^7$ tons/yr.[74] Mitigating 25 percent of this amount would require about five times the present production of in state limestone. The limestone resources of California are quite significant, however. The existing once-through cooling water is sufficient to mitigate about 10 percent of CO_2 produced without pumping any additional seawater. Economic analysis predicted a net cost of $3-30 per ton of CO_2 mitigated. If free limestone were not available, the cost would be in the range of $20-30 ton mitigated.

The cost estimates for the competing process of capture, purification, and underground storage of molecular CO_2 are in the range of $40-80 per ton of CO_2 mitigated when applied to conventional gas fired plants. Other competing technologies require materials naturally abundant which must be produced with significant cost and energy penalties.

2.20.5 Conclusions

The widely used ocean chemistry model from the literature predicts seawater chemistry under equilibrium conditions. The researchers found it deficient in its quantitative predictions under the non-equilibrium conditions present in the experimental flow reactor. This was not an unexpected result. While not as accurate in its predictions as desired, this objective was largely met.

The researchers found the rate of reactions between CO_2 and limestone in their first flow reactor was insufficient to convert dissolved molecular CO_2 to dissolved bicarbonate ion. These results required the reactor length to be extended, the limestone surface area to be increased with smaller particle size, and the residence time to be lengthened. These measures were successful in converting molecular CO_2 to bicarbonate and point the way to further research. At this early point in the development there were no adverse effects on sea life. Incubation of marine species over 35 days showed no statistically significant adverse effects on sea life due to alkalinity.

With the early stage data obtained, this approach to CO_2 sequestration in seawater appears to have the potential for lower cost than competing technologies. This conclusion is dependent on keeping both the cost of mining and transporting limestone and pumping additional seawater low. It appears that $20—30 per ton of CO_2 mitigated is within reach.

Cost estimates for the competing process of capture, purification, and underground storage of molecular CO_2 when applied to conventional gas fired plants are in the range of $40—80 per ton of CO_2 mitigated. Thus the proposed new technique appears to have an advantage. Other competing technologies suffer from not being naturally abundant and must be produced with a significant cost and energy penalty.

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74 Note that these plants operate at only a fraction of rated capacity. At rated capacity they would emit much more CO_2. http://www.opc.ca.gov/webmaster/ftp/project_pages/OTC/engineering percent20study/Executive_Summary.pdf

The main goal of this project was to determine the feasibility of using wet limestone scrubbing of flue gas to safely and cost effectively reduce CO_2 emissions from coastal power plants. The researchers demonstrated technical feasibility on a laboratory scale.

2.20.6 Recommendations

The Program Administrator recommends the researchers make more quantitative the rate of conversion of dissolved CO_2 to bicarbonate ion as a function of important operational parameters including limestone surface area, reaction length, and residence time. The researchers should substantially increase the length of the next generation experimental reactor in making these assessments.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.20.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

1. Reduced environmental impacts of the California electricity supply, transmission, or distribution system
2. Increased public safety of the California electricity system
3. Increased reliability of the California electricity system
4. Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California electricity supply, transmission, and distribution system. California has 16 coastal power plants powered by natural gas which are actively producing power and drawing seawater for cooling.[75] They have a combined capacity of 17.5 GW and at full capacity could produce 153,624 GWhr per year. At 1100 lbs of CO_2 per MWhr of electricity generated, these coastal plants yearly could emit up to 76.8 MMT of CO_2. Assuming a market penetration of 25 percent of coastal plant output, this technology could avoid emission of 19.2 MMT of CO_2, a significant benefit to California's efforts to reduce the environmental impacts of its electric system.

75 http://www.swrcb.ca.gov/water_issues/programs/npdes/docs/cooling/execsummary.pdf

2.20.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.20.8.1 Marketing/Connection to the Market

When this project was completed, the researchers had not yet found partners to aid in commercialization. They had not accomplished market assessment.

2.20.8.2 Engineering/Technical

The researchers stated it would require three to five years and a few million dollars to complete the engineering work necessary to go to market.

2.20.8.3 Legal/Contractual

The researchers reported they had applied for patents and had received one domestic patent, USP 6,890,497.

2.20.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

Because of the potential impacts on the environment, it is critical that the researchers conduct a thorough risk assessment and develop quality plans.

2.20.8.5 Production Readiness/Commercialization

Commercialization appears to be several years away. The researchers require partners to help them take this innovation to market.

2.21 Residential Integrated Ventilation Energy Controller

Awardee: EPB Consulting Group

Principal Investigators: Max Sherman

2.21.1 Abstract

This project assessed the feasibility of using a residential ventilation controller to reduce the energy impact of required mechanical ventilation by 20 percent while maintaining or improving indoor air quality and providing demand response benefits. The controller design was intended to meet the 2008 Title 24 requirements for residential ventilation by improving the efficiency of ventilating homes and advancing indoor air quality by minimizing intake of outdoor contaminants and reducing exposure indoors. The researchers sought to meet these objectives by allowing time shifting of ventilation and managing all of a residence's air systems such as kitchen and bath fans, exterior ventilated clothes dryers, etc. as an integrated system. In addition to reducing annual electricity consumption for ventilation, adoption of this approach in new residential construction in California could eliminate ventilation load during peak demand periods and reduce annual natural gas consumption. Savings for various types of new residential ventilation systems were simulated using models similar to those used to develop California's new residential ventilation requirements and were extrapolated from results of a two week field test of a prototype controller in a California residence.

Keywords: Residential ventilation efficiency, indoor air quality, ASHRAE Standard 62.2, Title 24

2.21.2 Introduction

California's adoption and implementation of aggressive standards for residential building air tightness have contributed to impressive energy savings and peak reductions. However, assessments of the resulting impact on indoor air quality have shown that some measure of supplemental ventilation beyond the remaining infiltration to the house is generally required. Relying on homeowners to open windows and doors for this purpose has been judged to fall short of the ventilation need. California's adoption of an ASHRAE (American Society of Heating, Refrigerating, and Air Conditioning Engineers) standard for residential ventilation[76] as part of the 2008 Title 24 energy standards sets the parameters for additional mechanical ventilation in new residential construction. This added mechanical ventilation could represent 5 percent to 32 percent of the total space conditioning load, depending on the system.[77]

Balancing the competing needs for reduced infiltration and indoor air quality can result in overall energy savings. For example, since the standards for added residential ventilation are relatively new in California, installations are typically not optimized to take advantage of occupants' operation of other sources of ventilation such as kitchen and bath fans and clothes dryers vented to the outside, nor are they able to time shift ventilation to provide demand response or to avoid periods of poor outdoor air quality. If all of a structure's ventilation were controlled as a single integrated system, savings in annual electricity, peak electric demands, and annual natural gas consumption would be possible.

The researchers proposed to determine the feasibility of using a residential integrated ventilation energy controller (RIVEC) to reduce the energy impact of required mechanical ventilation by 20 percent, maintain or improve indoor air quality, and provide demand response benefits. The principal focus of the project was simulation of a controller capable of operating the various air systems as an integrated system, including extrapolated annual savings from a limited duration field test of a prototype controller at a test house.

2.21.3 Objectives

The goal of this project was to determine the feasibility of using a ventilation controller to reduce the energy impact of required mechanical ventilation by 20 percent, maintain or improve indoor air quality, and provide demand response benefits. The project objectives and their associated performance metrics are summarized as follows:

1. Demonstrate that a residential integrated ventilation energy controller could save at least 20 percent of the annual energy needed for ventilation.

76 ASHRAE Standard 62.2-2007

77 Walker, I.S. and Sherman, M.H. 2008 "Evaluation of Existing Technologies for Meeting Residential Ventilation Requirements", LBNL 59998, Lawrence Berkeley National Laboratory, Berkeley, CA.

2. Demonstrate that the controller could remove 100 percent of the peak ventilation energy demand for up to four hours without harming indoor air quality.
3. Demonstrate that a hardware controller is capable of taking the inputs from an HVAC system and external conditions and controlling the variety of systems as outlined above.
4. Confirm that controller performs as expected to within 10 percent tolerance.
5. Confirm 20 percent annual savings for demonstration site. This objective contributes to the overall scope by demonstrating in an existing home that energy can be saved with a smart controller.

2.21.4 Outcomes

1. The researchers simulated the estimated RIVEC peak demand and energy savings for five types of ventilation systems in new residential construction using a model developed from prior work by Walker and Sherman. The systems were continuous exhaust, intermittent exhaust, heat recovery ventilator (HRV), central fan integrated supply with air inlet in return and continuously operating exhaust, and continuous supply. Researchers performed simulations for locations in Oakland, Fresno, and Mount Shasta, California. The only combination of climate and mechanical ventilation system that substantially missed the targeted 20 percent energy savings was an HRV in the cold Mount Shasta climate where overall gas consumption increased, leading to a net electric and gas savings of 13 percent.
2. The RIVEC controller program included capability to shut down mechanical ventilation during at least a four hour period. This period was set for the time of electrical peak demand for cooling and of peak heating load during the heating season. Programming the ventilation controller ensured sufficient mechanical ventilation at other times to make up for this off period, including use of an approximately 25 percent larger ventilation fan capacity.
3. The researchers successfully constructed a controller and used it in field tests. They measured and documented performance.
4. The mechanical ventilation system operating under the proposed controller was turned off for four hours (plus or minus 10 percent). During that time, the relative dose[78] was never more than 1.10 (i.e., 10 percent above what would nominally be expected by constant ventilation at the required rate).
5. The researchers selected a test home with a ventilation system and an economizer for the field demonstration. They tested the system over several weeks in late summer, with data collected for energy use, indoor and outdoor environmental conditions, and ventilation performance. After calibrating a simulation model for this house, the researchers used the test data to extrapolate annual performance. Results showed an

78 A measure of air quality.

estimated saving of over 60 percent of the nominal ventilation related energy and full compliance with indoor air quality standards.

2.21.5 Conclusions

The project demonstrated a significant potential for using the proposed system to reduce ventilation system peak electric and gas demands and energy consumption in new residential construction in California. The results supported the research objectives, and the final report provided an excellent background resource for further study and research. The design for this research relied primarily on simulations using well-documented models, with only limited field testing at a single location. As such, the conclusions below should be considered as work in progress pending further development of the ventilation controller, assessment of manufacturing and installation costs, and testing across a wider range of housing stock and climate zones over an extended time period.

The proposed controller could maintain indoor air quality while reducing the ventilation system's annual electric and gas energy consumption as well as peak electric and gas demand. Ventilation energy savings between 18 to 30 percent in a mild climate zone, 18 to 44 percent in a central valley climate zone, and 13 to 30 percent in a cold climate zone could be expected, depending on the ventilation system in place.

The proposed controller could save 100 percent of the ventilation system's peak power, while still maintaining required indoor air quality. Reductions in energy usage for cooling or heating could also be possible during these periods.

The researchers met this objective.

The field test data supported the conclusions described above for the limited sampling period and are a reasonable starting point for extrapolation of annual performance.

2.21.6 Recommendations

This project successfully demonstrated the potential for a fully developed ventilation controller to maintain indoor air quality. Outcomes were largely based on simulations. Given the researchers' extensive past research and publications employing simulations of energy systems, the logical next step is to emphasize further refinement of the controller design, assessment of manufacturing and installation costs, and more extensive field demonstrations at a number of typical residential locations with varying ventilation equipment over a longer time period. This work would form the basis for a more detailed assessment of the net costs and benefits of a commercial ventilation controller and how it might compare to less sophisticated approaches. The Program Administrator recommends exploring partnerships with home ventilating manufacturers and/or controls providers.

Since the requirement to include mechanical ventilation in new residential construction in California is relatively new, opportunities remain to improve on the codes and standards governing this requirement. Title 24, as well as ASHRAE Standard 62.2, should be expanded and clarified to address the role of control technologies to ensure a welcoming commercial market for these applications as they are commercialized.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.21.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

1. Reduced environmental impacts of the California electricity supply, transmission, or distribution system
2. Increased public safety of the California electricity system
3. Increased reliability of the California electricity system
4. Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. The results in this project suggest that if further development results in a successful launch of a commercial product, ventilation electricity consumption in new residential construction could be reduced by roughly 20 percent. Because of the new requirement for mechanical ventilation, a baseline number for energy consumption of the new ventilation systems is not available for California.

2.21.8 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.21.8.1 Marketing/Connection to the Market

California's adoption of residential ventilation standards in 2008 Title 24, as well as continuing work on ASHRAE standard 62.2, have created an immediate market for products which can optimize the balance between the need to reduce air infiltration and preserve indoor air quality in new residential construction.

2.21.8.2 Engineering/Technical

The research was focused on proof of concept, largely through simulations. Although the researchers built and tested a prototype controller, further engineering and technical development is necessary prior to product introduction. The researchers did not indicate if any of this work was underway or planned.

2.21.8.3 Legal/Contractual

Patents had not been pursued, although the researchers indicated they had protected proprietary information needed to secure a patent.

2.21.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

The environmental benefits of RIVEC would accrue directly from reduced electricity and natural gas consumption for space conditioning. Once the controller design has been finalized, the researchers should conduct risk assessments and develop quality plans for the product.

2.21.8.5 Production Readiness/Commercialization

The researchers did not provide a commercialization plan. Additional development work is necessary before the concept is production ready.

2.22 Feasibility Analysis of Cleanroom Airflow Reduction Based on Establishment of Theoretical Basis and Required Validation

Awardee: Engsysco, Inc

Principal Investigators: Wei Sun

2.22.1 Abstract

The goal of this project was to determine the feasibility of cleanroom air change rate reduction based on establishment of a theoretical basis and required validation. Presently cleanroom airflow design is based on historical standards lacking scientific basis. The decades old standard FS-209 and IEST Recommended Practices RP-12 and the more recently published ISO 14644-4 standard (2001) specify a required number of air changes per hour (ACH) based on a cleanliness class identified by a maximum allowable particle concentration per cubic foot. Higher ISO class designations indicate a lower particle concentration that requires a higher ACH. Although it is intuitive that a higher ACH would result in a lower particle concentration, the ranges specified are arbitrary, based on historical rules of thumb, and are considered worst case scenario requirements. The researchers proposed to develop a mathematical model that could calculate the required airflow based on numerous variables, including:

1. Room air particle concentration. For example, a room designed for Class 10,000 would have maximum particle concentration of 10,000 particle counts per ft^3 at 0.5 μm.
2. Outside air particle concentration.
3. Exposed surface particle concentration (deposition).
4. Room particle generation rate.
5. Efficiencies of all filters, including supply air HEPA filter.
6. Outside air as a percentage of supply air.
7. Return or exhaust air as a percentage of supply air.
8. Leakage air as a percentage of supply air. Leakage air causes either gain or loss particles.

9. Room dimensions height, width, and length.
10. Room temperature and relative humidity.

The researchers anticipated that theoretical determination of the required airflow rate, rather than use of worst case scenario requirements, could lead to a reduction in required airflow of approximately 20 percent over current standards. The savings in fan energy, if applied to the estimated 10 million square feet of cleanroom space in California, could lead to an average yearly energy savings of 910,000 MWh. This technology could be applied to both current and planned cleanrooms in determining an optimum airflow rate given a target cleanliness standard.

Keywords: Cleanroom, modeling, air change rate, particle concentration, surface particle deposition, HVAC, filtration

2.22.2 Introduction

Cleanrooms use between 5 and 50 times the airflow rate required for general purpose buildings to maintain cleanliness standards. United States Federal Standard FS-209 (1963) was the first standard issued for cleanroom classification. It determined cleanroom classifications based on the number of airborne particles greater than 0.5 μm per cubic foot. This standard was retired in 2001 upon the adoption of the international standards ISO 14644-4 and related standards ISO 14644-1 and 14644-2. Cleanroom standards dictated the required airflow changes per hour (ACH) based on historical practice, rather than scientific determination. This lack of scientific determination has led to concern of filtered air over supply and related energy waste.

In recent decades as cleanroom design technologies have improved many designers have experimented and successfully decreased the airflow rate by 20 to 30 percent of the recommended ACH in ISO standards while maintaining the same level of cleanliness.[79,80,81] These experimental efforts are not widespread and results are rarely implemented, given the perceived risk associated with adopting lower than recommended airflow rates. Although the studies have indicated particle concentration targets can be met with lower ACH, this has not been scientifically proven, nor has any research been performed which might provide a scientific basis for airflow recommendations.

The researchers in this project conducted a literature review to identify existing mathematical airflow models. All models identified were qualitatively based, over simplified, and lacked

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79 Jaisinghani, R. A. 2001. InterPhex Conference, March 20-22, Philadelphia, PA. "Air Handling Considerations for Cleanrooms."

80 Kozicki, M., P. Robinson, and S. Hoenig. 1991. "Cleanrooms, Facilities and Practices."

81 Sun, W, 2003. CleanRooms, December Issue, 2003, "Trend Toward Cleaner Auto Facilities Is Accelerating."

experimental justification. To overcome these shortfalls, the researchers proposed a new quantitative model including numerous variables previously omitted or ignored which could be validated through scientific experimentation. This model captured time as a variable to include both transient and steady state applications. The model development was based on the commonly used HVAC configuration, a conventional primary loop air handling system. However alternate configurations could be accommodated through use of a combined efficiency, E_u, which includes the efficiency of all filters installed in series. Figure 25 shows typical HVAC configurations for cleanrooms. The simplified model in steady state is as follows:

$$C_{ST} = \left(\frac{b}{a}\right) \cdot C_o = \frac{(1 - E_U) \cdot (1 - E_H) \cdot m \cdot C_O + \dfrac{(1 - \theta) \cdot G}{ACR}}{m + (E_U + E_H - E_U \cdot E_H) \cdot (1 - m)}$$

Where,

C_{ST} = Impurity concentration at any time in space (parts/volume)

C_{SO} = Initial impurity concentration in space (parts/volume)

C_O = Impurity concentration in makeup air (parts/volume)

E_U = Filter combined efficiency in AHU unit

E_H = HEPA filter efficiency in room

G = Rate of impurity generation in space, averaged throughout the space (parts/volume/time)

θ = Percentage of total particle generation deposited on exposed surfaces

m = Ratio of Outside Air (OA) and Supply Air (SA), OA/SA

ACR= Air Change Rate ($time^{-1}$)

D* = Rate of impurity deposition from air to surface in space, averaged throughout the space (parts/volume/time)

SA*= Supply Air Volumetric Rate (volume/time)

RA*= Return Air Volumetric Rate (volume/time)

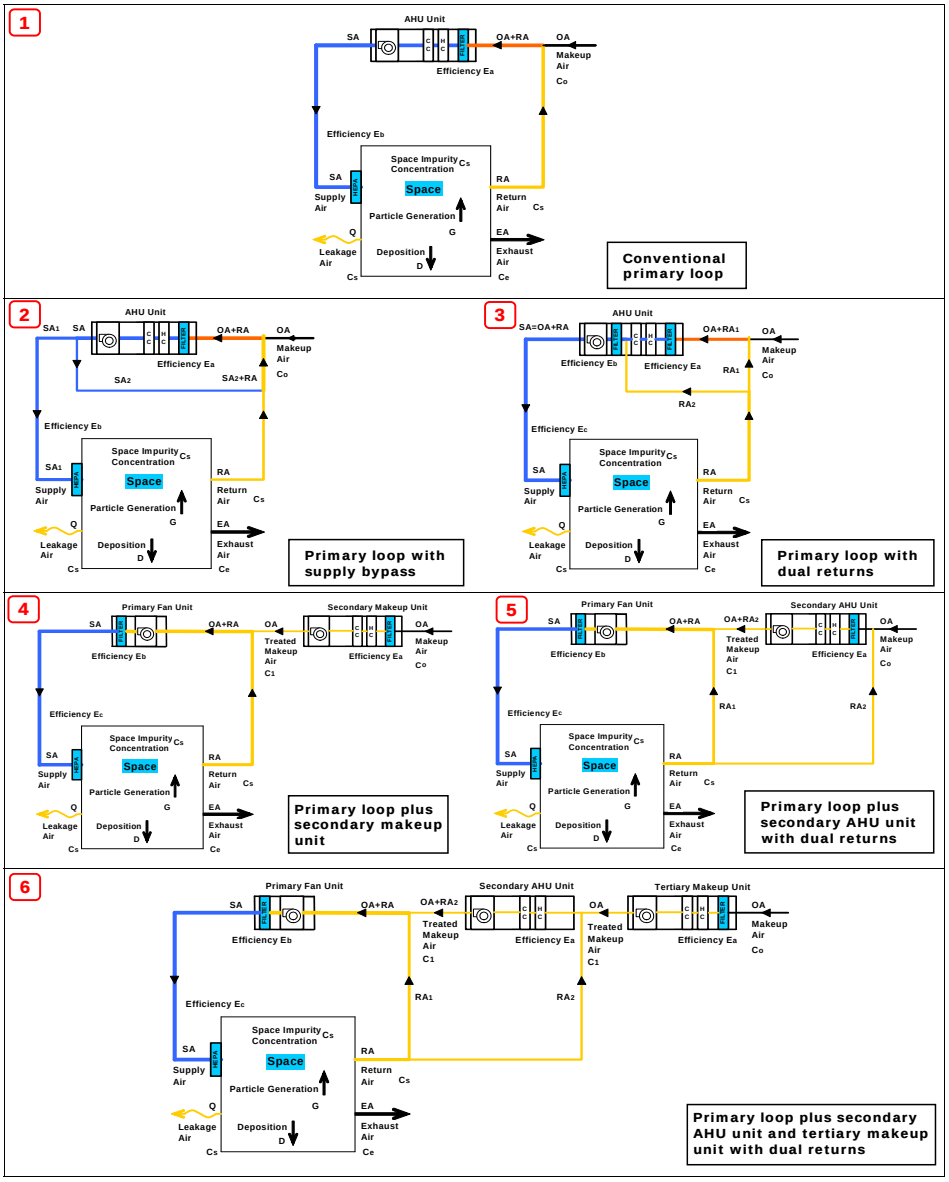
EA*= Exhaust Air Volumetric Rate (volume/time)

* Variables shown in Figure 25 and included in researchers' case model.

Adoption of a scientific model to quantitatively determine the required ACH for a desired particle concentration would result in a significant energy savings over the worst case scenario approach codified in current standards. The total estimated cleanroom floor area in California

today is 10 million square feet. Using estimates from Mills et. al.,[82] this translates to approximately 6,000 GWh per year with a peak use at 1,450 MW. If scientific justification can lend support to earlier findings that cleanliness standards could be maintained with a 20 percent ACH reduction, the state of California could realize a 20 percent energy savings or approximately 1,200 GWh per year.

Figure 25: Typical Air Handling System Configurations for Cleanrooms



82 Mills, E, G. Bell, D. Sartor, A. Chen, D. Avery, M. Siminovitch, S. Greenberg, G. Marton, A de Almeida, and L.E. Lock. 1996. Energy Efficiency in California Laboratory Type Facilities. Lawrence Berkeley National Laboratory Report, LBNL-39061. Link: HUhttp://eetd.lbl.gov/EA/mills/emills/pubs/LabEnergy/LabEnergy.pdfU

2.22.3 Objectives

The goal of this project was to determine the feasibility of cleanroom air change rate reduction based on the establishment of a theoretical basis and required validation. The researchers stated an average of 20 percent fan energy reductions in cleanrooms could be achieved. They established the following project tasks and objectives:

Establish a new model to calculate the air change rate using differential equations. Compare the model with existing models. The new model should be more descriptive and include more variables and parameters. The new model should be more accurate than existing models as measured by the difference between the predicted and tested data.

Conduct demonstration tests. Measure room particle concentration at each condition (respective air change rate and other variables and parameters), then plot the predicted and measured results for each condition. Identify trends and apply a correction factor if needed for refinement. Demonstrate a good correlation between the predicted and measured results. Narrow the gap between the predicted and measured results using correction factors.

Analyze the model by varying each variable and parameter in the new model to test its impact to the room particle concentration change. Produce related charts and tables. Demonstrate the relative significance (effect) of the related variables and parameters to the air change rate requirement in terms of fan energy consumption.

Provide recommendations and identify the options to reduce the air change rate in cleanrooms based on the new model. Demonstrate a group of cost effective approaches to lower the air change rate to reduce fan energy consumption. Demonstrate the advancement of air change rate recommendation above existing guideline.

2.22.4 Outcomes

The researchers provided a concise summary of existing models dating to the earliest cleanroom standards, identifying relevant input parameters in existing and proposed models. Using the assembled input parameters, they derived a differential equation to calculate the air change rate for the transient state as well as the steady state. They simplified and modified this model for use in numerous cleanroom HVAC configurations with either pressurization or depressurization. They performed parametric studies for variations in particle generation rate, final filter efficiency, combined filter efficiency, outdoor air intake particle concentration, outdoor air percentage of supply air, and surface particle deposition rate.

The researchers used three separate cleanrooms to conduct demonstration testing. They took measurements of outside air particle concentration and exposed surface particle concentration and calculated the supply ACH. Parametric studies evaluated variations in supply air filter efficiency; room particle generation; and outside air, return air, exhaust air, and leakage as a percent of supply air. With each variation, the researchers predicted the room particle concentration using the model and compared this to measured values.

The researchers performed numerous experiments to isolate variables within the model. At various ACH rates, they conducted experiments to investigate the space velocity profile under

various flow patterns, particle size and concentration, particle migration under pressure differentials, impact of particle migration as a result of leakage, surface particle deposition, and filter efficiency. Although they did not perform error analyses, they did estimated uncertainty for each of the model component variables based on manufacturer data, specifications, or published data.

Using the results of experiments performed for Objective 3, the researchers provided a comprehensive list of recommendations that would optimize model parameters such that ACH could be minimized while maintaining desired cleanroom cleanliness. The researchers acknowledged that the model focused on the common range of nonviable particles currently regulated by ISO standards and would not apply to nonparticulate chemicals in gas/vapor states or sorbed states or microbial contamination. These particles would require additional modeling.

2.22.5 Conclusions

The researchers met the objective to establish a quantitative model to calculate the air change rate. The model included all variables identified by the researchers based on their literature review and experience in cleanroom design. The model correlated well to the measured data in both low flow and high flow settings when a correction factor of 0.3 was applied.

The researchers met the objective to conduct demonstration tests to validate the numerical model. A correction factor of 0.3 was required to provide better correlation between predicted and measured values. The researchers acknowledged their study did not include error analysis and recognized discrepancies between measured and predicted values could be attributed to calibration of test instruments, particle sensor positions and elevations, stability of particle generation, sampling speeds of data acquisition, and other factors. Although graphically presented without statistical interpretation, the correlation between measured and predicted appears to be significant at both high and low flow ACH ranges. The large correction factor needed to obtain this correlation warrants further investigation.

Although the researchers met the objective to analyze the model under varying conditions, they did not translate their findings into effects on fan energy consumption and a potential for savings when compared to existing standards requirements.

The researchers met the objective to provide a set of cost effective approaches to lower the ACH in consideration of fan energy consumption. Although a quantitative approach to determination of ACH is advancement over prior qualitative approaches, the researchers did not demonstrate the improvement in terms of potential energy savings.

2.22.6 Recommendations

The researchers were able to achieve the overall project goal, but not definitively translate the research goals into cost savings for California. The researchers' final report Chart 6, a comparison of the new model based ACH versus IEST recommended ACH, was the starting point from which the cost savings comparison could be quantified, yet the actual reductions in airflow that could be realized when using the new model vs. the old model were not addressed in detail. Rigorous and detailed interpretation of Chart 6 might have accurately led to the

conclusion that the current standards require 20 percent more ACH than is necessary, but this is not readily apparent. Rather, it appears the researchers relied upon work performed by others in suggesting that cleanliness standards were maintained during operation with a 20 to 30 percent reduction in airflow velocity. Presumably the new model would be able to quantify the findings of these qualitative studies, thus validating the 20 percent savings. Quantification of the actual potential savings using case studies or realistic parameter values seems the last significant hurdle in justification of the pursuit of this technology. Assuming this model will provide reductions in ACH over current standards, the researchers appear well placed to affect change in an arena that has avoided scientific intervention for decades.

As part of continued development of this technology, the Program Administrator recommends the following tasks be completed:

1. Conduct studies to quantify ACH recommendations in comparison to current regulations and determine a percent savings as a function of room cleanliness for each of the regulated cleanroom classes using case studies or average parameter values.
2. Perform an error analysis and investigate the source of errors necessitating a 0.3 correction factor for the numerical model.
3. Conduct Monte Carlo sensitivity analysis for model parameters.
4. Identify political barriers to adoption of a quantitative standard for determination of ACH.
5. Pursue submission of a new draft standard for ACH determination based on the proposed model.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.22.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

1. Reduced environmental impacts of the California electricity supply, transmission, or distribution system
2. Increased public safety of the California electricity system
3. Increased reliability of the California electricity system
4. Increased affordability of electricity in California

The primary benefit to the ratepayer from this research could be increased affordability of electricity in California. Studies performed by others suggest that cleanliness standards can be maintained during operation with a 20 to 30 percent reduction in airflow velocity over recommended standards. Because these studies were qualitative, practitioners are reluctant to reduce fan speeds to realize this savings. Updating the standards through the use of the proposed quantitative model would provide justification for reduction in fan speeds. The total estimated cleanroom floor area in California is 10 million square feet. Estimates from Mills et. al. (1996) translate to approximately 6,000 GWh per year with a peak use at 1,450 MW. If scientific justification can lend support to earlier findings suggesting that cleanliness standards could be maintained with a 20 percent ACH reduction, California could realize a 20 percent energy savings, or approximately 1,200 GWh per year.

2.22.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.22.8.1 Marketing/Connection to the Market

Dr. R. Vijayakumar, one of the co-investigators, is a Vice-President of IEST and is thus well placed to affect change in cleanroom standards. The code writing group within IEST has indicated a willingness to adopt a quantitative standard once it is validated. This technology is applicable to all cleanroom settings.

2.22.8.2 Engineering/Technical

The researchers plan to continue error and sensitivity analysis to refine the numerical model. They plan compilation of a software program to make implementation of the model easier, but this will require significant funding. There are presently no technical barriers to implementation of this technology.

2.22.8.3 Legal/Contractual

The researchers have performed a search for patents, but have not yet filed for patent protection. The numerical model has been published for public domain, but the software implementation of the model will be protected under patent.

2.22.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

Because of technology immaturity, these plans have not been developed.

2.22.8.5 Production Readiness/Commercialization

The researchers plan to pursue commercialization of this technology and are seeking additional funding for full-scale testing and software development.

2.23 Carbon Molecular Sieve with Tunable Properties

Awardee: University of Southern California

Principal Investigators: Theodore T. Tsotsis

2.23.1 Abstract

Carbon molecular sieve (CMS) membranes are potential candidates for carbon capture. They have resistance to high temperatures and pressures, such as those involving gas mixtures containing CO_2, H_2, and CH_4. The goal of this investigation was to study these membranes in model applications that involve the separation of these gases in the context of power generation. They include CO_2 separation from flue gas (post combustion CO_2 capture) and H_2 separation from reformate and water gas shift mixtures (pre combustion capture). This study investigated novel preparation techniques to adjust the membrane average pore size and to modify its surface characteristics (affinity towards selected compounds). The techniques investigated involved activating the carbon structure using steam and/or methane and incorporating metal nanoparticles within the membrane structure. The researchers characterized the transport and separation properties of the resulting CMS membranes in terms of their permeabilities and ideal permselectivities using single gases such as H_2, CO_2, and CH_4. The preliminary results demonstrated proof-of-concept, but whether such CMS membranes would work under field conditions and the determination of the cost to use such technology for practical applications require additional research.

Keywords: Carbon molecular sieve membranes, steam and methane activation, metal nanoparticles

2.23.2 Introduction

Carbon capture and storage (CCS) from point source emissions has been recognized as one of several strategies necessary for mitigating release of greenhouse gases into the atmosphere. Monoethanolamine (MEA) solvent extraction is the most developed and researched CO_2 separation technology. However it suffers from high energy use. Power plants that generate electricity from carbon based fuels may be required to separate CO_2 from flue gas streams. Chemical routes to hydrogen production from coal and natural gas can be enhanced with CO_2 separation. This could be simplified with the availability of CO_2 selective membranes.

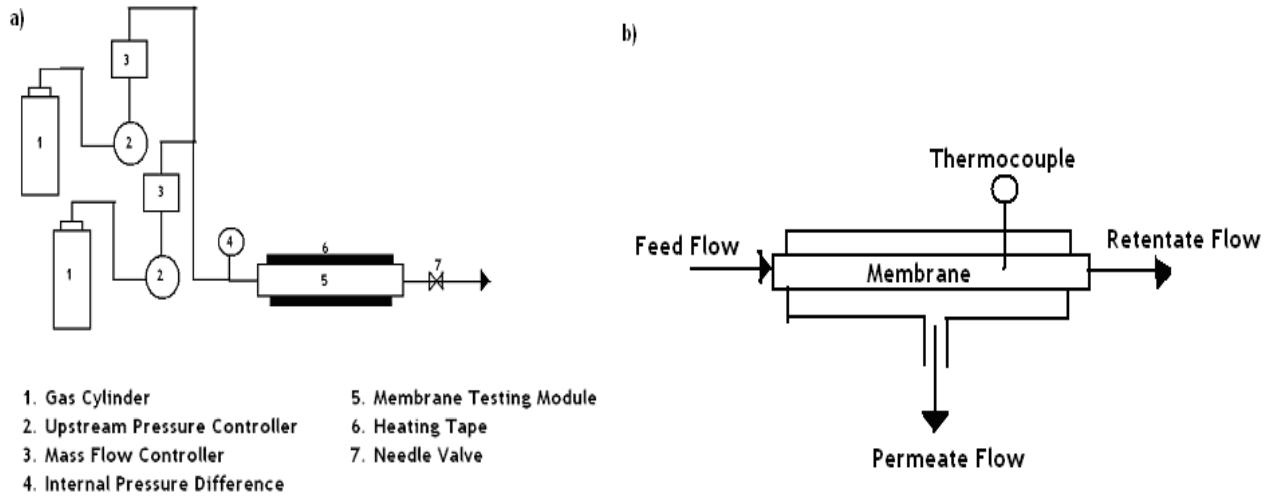
Membrane separation shows promise for application in CO_2 capture in power generation systems, but it faces challenges before this process will be used widely in power generation. Membrane performance in terms of selectivity, throughput, and cost must be improved. Membranes can be applied to the three key separation operations involved in CO_2 capture in power generation systems, namely CO_2 separation from flue gas (post combustion capture), H_2 separation from reformate and water gas shift mixtures (pre combustion capture), and O_2/N_2 separations (oxy fuel combustions). In contrast to polymeric membranes, carbon molecular sieve (CMS) membranes are chemically inert but versatile in their pore structure characteristics and do not face the materials degradation issues associated with polymeric membranes. They can also show good performance towards selected gas separations (e.g., H_2/CH_4 and H_2/CO).

However their performance characteristics towards other gas separations (H_2/CO_2, CO_2/CH_4, O_2/N_2, or multi gas mixtures) are still rather moderate.

In this project researchers investigated novel techniques for tuning carbon micropore sieves to improve their selectivity and permeance to CO_2 and related gasses.

Figure 26 below illustrates the concept.

Figure 26: a) Schematic Diagram of the Experimental Apparatus b) Schematic Diagram of the Membrane Testing Module



2.23.3 Objectives

The goal of this project was to determine the feasibility of developing an effective technique for preparing CMS membranes with tunable properties for use in CO_2 capture and sequestration from stationary power plants. The goal was to be able to independently tune the pore size and the surface affinity of these membranes. The researchers established the following project objectives:

1. Investigate steam activation and surface modification as means for tuning the membrane properties of CMS membranes. Prepare membranes with pore sizes in the range of 3 to 7 angstroms (Å).
2. Test membranes with respect to their separation characteristics: H_2/CO_2 –target 10, H_2/N_2 –target 50, and O_2/N_2–target 20.
3. Evaluate the economics of their application.

2.23.4 Outcomes

The researchers prepared and measured the transport characteristics of steam activation and surface modification means for tuning the membrane properties of CMS membranes. They prepared microporous membranes with pore sizes in the range of 3 to 7 angstroms (Å).

The researchers characterized the membranes in terms of the flux through the membrane using single gases. They also measured the transport properties of these membranes using specific gas mixtures (H_2/CO_2 and H_2/CH_4–methane being used as a surrogate for all inert large molecules such as CO and N_2). Representative results for one fabrication technique are shown in Table 3.

Table 3: Permeances (m3/m2*bar*h) and Separation Factors Measured at 150°C for Membranes Subjected to Methane Activation (M-B1)

	Membrane 1 (at 650 °C)			Membrane 2 (at 700°C)		
	Before	After	Change	Before	After	Change
H_2	1.059	0.258	-76 percent	1.572	0.161	-90 percent
CO_2	0.610	0.046	-92 percent	0.648	0.016	-98 percent
CH_4	0.073	0.054	-26 percent	0.088	0.071	-19 percent
$S(H_2/CO_2)$	1.7	5.6	229 percent	2.4	10.0	317 percent
$S(H_2/CH_4)$	14.5	4.7	-68 percent	17.9	2.3	-87 percent

The researchers evaluated the economics of using the membranes prepared for a post combustion CO_2 capture and sequestration application. Based on their findings, increasing the permeance of CO_2 significantly reduced the required membrane area, as would be expected. The capital costs for a commercial operation would be highly dependent on the surface area of the membrane: the larger the membrane area the higher the cost. The researchers estimated commercial level costs neither for the membrane(s) nor for a complete system. Also, they did not estimate operational costs.

2.23.5 Conclusions

The researchers demonstrated the ability to tune CMS membranes for selectivity and permeance to CO_2. The early stage of this concept suggests that technical feasibility is possible, but not yet proven since significant development needs remain. Cost competitiveness of this approach compared to MEA solvent extraction and other means of capturing CO2 remains unclear. The tolerance of pore size and transport properties to small changes in treatment conditions will affect performance of commercially produced CMS membranes since the 3 to 7 angstrom window is small.

2.23.6 Recommendations

Selectivity and permeance under typical power plant flue gasses need to be established, and the researchers should focus on one or two select tuning techniques. They should undertake physical testing of the membranes to evaluate durability and toughness. This will be critical to designing of an operational system. The researchers should continue to improve the selectivity and permeance of chosen membranes and determine their thermal characteristics and tolerance, including under mixed gas stream conditions. The researchers should investigate the tolerance of CMS membrane pore size and transport properties to changes in treatment conditions, with an eye towards quality assurance in ultimate commercial applications. They should undertake testing and demonstration with gas streams containing acid gasses to ensure quality performance is maintained for extended periods.

The researchers should undertake a more complete economic analysis and evaluate cost and performance tradeoffs for both membranes and balance of system. Marketing plans and activities should focus on competitive advantages of tunable CMS based carbon capture compared to other (e.g., polymeric, solid oxide) selective membranes. While monoethanolamine (MEA) solvent extraction is the most developed and researched separation technology, it suffers from high energy use. Consequently other techniques in the early research stage, as is this one, are fighting for ultimate market dominance.

2.23.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

1. Reduced environmental impacts of the California electricity supply, transmission, or distribution system
2. Increased public safety of the California electricity system
3. Increased reliability of the California electricity system
4. Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California electricity supply system.

The major drawback of solvent scrubbing is the high cost due to the high energy requirements of the process. The energy required using monoethanolamine (MEA) as a solvent (the most developed technology) can cause a 20 percent reduction of power generation for a coal fired facility.[83] Addition of an amine scrubbing CO_2 capture plant would reduce the efficiency by 21 percent to 36 percent, due to cooling and then reheating both the solvent and flue gas. The concept that was the subject of this research could significantly reduce the efficiency penalty compared to amine based carbon capture, depending on the membrane based system's operating temperature and permeance.

83 http://www.iea-coal.org.uk/site/ieacoal_old/publications/newsletter/current-issue-a/newsletter-3?

In 2008 California generated 122,000 GWh of electricity using natural gas. If this concept were successfully applied to all current natural gas fired facilities, assuming they would otherwise be retrofitted or replaced, an additional 21,000 to 44,000 GWh might be available with no increase in natural gas use. A reasonable penetration achievable in 25 years might be 10 percent of the existing capacity or the equivalent of 2,100 to 4,400 GWh.

2.23.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.23.8.1 Marketing/Connection to the Market

The researchers determined that their innovation would best serve in the industrial sector. They have a working relationship with Media and Process Technology, Inc. of Pittsburgh, PA. The researchers anticipate that Media and Process Technology, Inc. will take the innovation to market.

2.23.8.2 Engineering/Technical

The researchers anticipate they will need an additional five years of engineering work and an additional $250,000 to $500,000 to complete product development and demonstration.

2.23.8.3 Legal/Contractual

The researchers have not applied for a process patent on the technique for tuning CMS membranes for carbon capture application. They are in early discussions with commercial firms to develop and market the technology, but no contracts or agreements have been signed.

2.23.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

There are no known environmental or safety risks associated with the technology.

2.23.8.5 Production Readiness/Commercialization

Production and commercialization plans are premature until the technology advances described above are successfully achieved. It is likely that Media and Process Technology, Inc. will take successful results of this project to market.

2.24 Solar Thermal Heat Pump/Chiller

Awardee: Energy Concepts Company, LLC

Principal Investigator: Donald Erickson

2.24.1 Abstract

Providing space conditioning and hot water for commercial buildings is a major energy cost and consumer of carbon based fuels. These end uses represent about 35 percent of a typical commercial building's energy use. Using solar energy to provide these end uses would significantly reduce fuel use, but solar energy remains costly to building owners. This project built and tested a prototype of a dual function solar thermal heating and chilling product. The researchers named the device the Helisorber™. This solar thermal heat pump/chiller provided

hot water at a claimed 60 percent higher efficiency than any existing solar heating product while it simultaneously produced chilled water.

The goal of this project was to build and test a solar thermal heat pump/chiller with a design heating coefficient of performance (COP) of 1.6 and a chilling COP of 0.6. The project involved the design, fabrication, and testing of a solar thermal heat pump/chiller that produced 800 thousand BTU per hour heating and 25 tons chilling from 500 thousand BTU per hour thermal input. The test results confirmed that the target performance is achievable with a 240°F solar heat source. That temperature is available from relatively low cost solar collectors.

Tests indicated that the proposed solar thermal heat pump/chiller should provide energy savings even when powered by a backup boiler. This eliminates the need for any solar thermal storage. It does not require a cooling tower since the heat rejection is to the hot water. (This assumes that the hot water is put to beneficial use.) Both of these features may contribute to low system cost. A cost estimate of the complete system including backup gas fired heater, piping, and controls indicated a simple two to four year payback.

Keywords: Renewable energy, Helisorber™, solar, absorption, chilled water, hot water, thermal energy, cooling, heating, solar thermal heat pump/chiller

2.24.2 Introduction

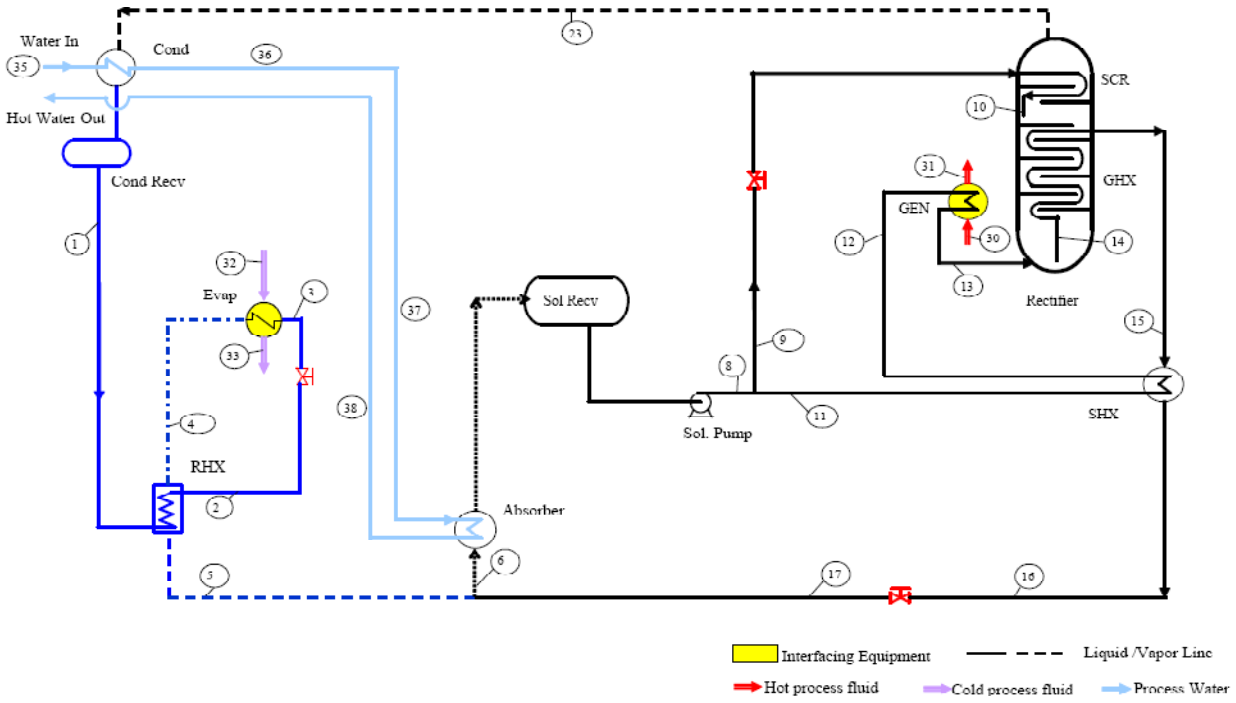
Providing space conditioning and hot water for commercial buildings is a major energy cost and consumer of fossil fuels. These end uses represent about 35 percent of a typical commercial building's energy use.[84] Using solar thermal energy to provide these end uses could significantly reduce fuel use and associated carbon emissions, but solar energy systems remain costly to building owners.

Solar energy promises a potential means of reducing natural gas and electricity used for water heating and space conditioning. Currently, most solar thermal applications provide chilled water or hot water, but not both. Expensive solar collectors for single functionality make solar energy expensive and inefficient, resulting in poor consumer acceptance. With dual functionality and a single collector field, a more economical solar thermal technology may provide a competitive alternative to traditional natural gas and electric systems and enhance consumer acceptance.

This project involved the design, fabrication, and testing of a solar thermal heat pump/chiller rated at 25 refrigeration ton (RT) chilling. The design used heat pump technology to simultaneously produce chilled water and heated water with a solar heat source near 240°F. This input temperature permitted the use of relatively low cost, low concentration collectors. The researchers fabricated the solar thermal heat pump/chiller on a compact skid and proved feasibility. See Figure 27.

84 http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/bt_stateindustry.pdf

Figure 27: Solar Thermal Heat Pump/Chiller



2.24.3 Objectives

The goal of this project was to demonstrate the feasibility of converting solar thermal energy to a combination of chilled water plus hot water with a solar thermal heat pump/chiller. The researchers established the following project objectives:

1. Demonstrate thermodynamic feasibility of the desired performance: COP 0.68; 240°F solar heat; 44°F chilled water; 130°F hot water.
2. Achieve footprint of three foot by three foot for a 25 refrigeration ton (RT) solar thermal heat pump/chiller.
3. Confirm unit achieves design specifications with variable solar insolation and hot water loads.
4. Confirm device can be readily manufactured and demonstrate mechanical feasibility.
5. Confirm net installed cost of $5,000/RT (or less) and three to five year payback.

2.24.4 Outcomes

1. The researchers designed an ammonia-water single effect absorption cycle for a solar thermal heat pump/chiller providing 25 RT of chilling while co-producing hot water at 130°F (from 70°F) with solar heat of 240°F. The chiller was to reduce the temperature of a water/glycol mixture to 44°F from 55°F. The researchers developed specifications for all system components.

2. The researchers developed a detailed layout of the system showing principal dimensions, relative location of components, interconnecting piping, instrumentation, and controls. The footprint measured 44 inches by 30 inches.

3. The researchers reported that the thermodynamic design confirmed the feasibility of the solar thermal heat pump/chiller providing 25 RT of chilling, cooling water/glycol from 55°F to 44°F, and co-producing hot water at 130°F (from 70°F) with solar heated fluid at 240°F. The prototype solar thermal heat pump/chiller performed essentially as designed. With 240°F solar heated fluid, the solar thermal heat pump/chiller delivered 130°F hot water at a COP of 1.6 and 44°F chilled water at a COP of 0.6. The researchers optimized various components and lowered the target cycle efficiency slightly resulting in a final design cooling COP of 0.655. The researchers found that the performance was significantly dependent on two components – the solution heat exchanger and the absorber. A multi-pass solution heat exchanger and a custom shell and coil absorber met design performance criteria.

4. The researchers designed the hot water and coolant loop load interfaces, solar collector and backup natural gas fired heater tie-ins, and control system. They fabricated proprietary components. They specified and procured standard heat exchangers, pumps, and instrumentation. The fabricated and procured components and instrumentation were assembled onto a skid.

5. The researchers developed a test program to verify overall system performance at design conditions and corresponding startup and shutdown sequencing. They tested the solar thermal heat pump/chiller prototype under nine sets of conditions.

6. The researchers estimated the manufacturing cost of the solar thermal heat pump/chiller at $44,000 not including solar collectors. They completed a preliminary economic analysis using the cost estimate and performance results. The researchers estimated the simple payback for representative markets at between two and four years.

2.24.5 Conclusions

1. The researchers optimized the system design at a chilling COP of 0.655. The design indicated that the performance was significantly dependent on the absorber.

2. The 25RT solar thermal heat pump/chiller had a footprint of 44 inches by 30 inches, which was compact yet provided maintenance access.

3. The heat pump/chiller may provide significant energy savings and economic benefits to the State of California. The developed system could be efficient when operating with a backup boiler. A nominal capacity solar storage tank may be needed for optimal solar energy utilization and to minimize cycling.

4. The researchers employed fabrication techniques amenable to low cost mass production of proprietary components and a compact skid.

5. Tests confirmed that the solar thermal heat pump/chiller could simultaneously provide

hot water and chilled water from a solar heat source in the range of 240°F to 250°F. Most of the components and controls performed at or above design specifications. The solution heat exchanger and absorber performed below design specification. Upgrading these components may help achieve full design performance. Cost estimation of the complete system confirmed a three to five year payback.

The researchers proved the feasibility of simultaneously providing chilled water and hot water from a single solar collector array.

2.24.6 Recommendations

1. The Program Administrator recommends:
2. The researchers should initiate a market requirements study to determine the thermal needs of industries that might use the solar thermal heat pump developed in this project. The study should determine the time of day that the thermal energy is needed (both chilling and heating), the temperature requirements for the applications, and the total thermal energy needed per hour. The data from those studies should be matched to the projected outputs of the solar thermal heat pump/chiller in that climate zone. An economic analysis should include a backup system to determine true economic value.
3. If the market study indicates a strong physical and economic need for a solar thermal heat pump/chiller with the outputs demonstrated in this project, the researchers should arrange a field demonstration program. The field test units should be deployed in various climate zones in California to validate the economic benefits.
4. The researchers should develop manufacturing plans and marketing and installation guides.
5. After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.
6. Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.24.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

1 Reduced environmental impacts of the California energy supply, transmission, or distribution system

2 Increased public safety of the California energy system

3 Increased reliability of the California energy system

4 Increased affordability of energy in California

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California energy supply and distribution system.

Lodging, food service, and health care use 79 trillion BTU of natural gas per year in California. Of this, 53.5 trillion BTU is used for space and water heating. The largest natural gas customers in these three industries use 25 percent of the total energy consumed.[85] The researchers expect to achieve about 25 percent market penetration in this size range. They predict savings of 3.68 billion BTU per year of natural gas and 148,750 kWh per year per heat pump unit. A 25 percent market penetration represents an installed base of over 900 solar thermal heat pump/chillers with a chilling capacity of 25 RT within ten years. At that level of penetration the solar thermal heat pump/chiller would save 3.3 trillion BTU (900*3.68 billion BTU) of natural gas per year in California plus reduce the consumption of 134 million kWh (900*148,750 kWh) of electricity. The reduction in CO_2 emissions associated with the 3.68 billion BTU savings in natural gas consumption per 25 RT solar thermal heat pump/chiller is estimated at 195 metric tons of carbon per year (3.68 billion BTU *53.05 ton CO_2 per billion BTU).[86]

The market penetration estimates and energy savings described above rely on a match between the thermal needs of an industry or institution and the thermal output of the solar thermal heat pump/chiller. The demand and output must match on temporal, temperature, and total energy bases to achieve full benefits. Thermal energy at 130°F has little value in many applications besides space heating and domestic hot water. If a facility needs a lot of space heating at this temperature, it may not need all of the chilling. On the other hand, much of the built up areas of California require more space cooling than space heating. Without a use for the heated water, users of the solar thermal heat pump/chiller described in this project may have to install cooling towers to reject the excess heat. Hospitals often need higher temperature water or steam to sterilize bedding, gowns, and medical equipment. Few industrial processes require water at temperatures as low as 130°F.

2.24.8 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.24.8.1 Marketing/Connection to the Market

Energy Concepts Company has established a manufacturing capability able to manufacture approximately 100 of the 25-ton Helisorbers™ per year, which would cover the anticipated demand for the product for the first two or three years. Energy Concepts Company is working with PG&E, SoCal Gas, and Desert Power in California to commercialize the related

85 US Energy Information Agency, "A Look at Commercial Buildings in 1995: Characteristics, Energy Consumption, and Energy Expenditures." Washington, D.C., 1998.

86 California Energy Commission, "Guidance to the California Climate Action Registry: General Reporting Protocol." Committee Report P500-02-005F, 2002.

Thermosorber™ product in California, which may accelerate the adoption of the solar configuration. They are also in discussions with solar collector manufacturers for potential partnership(s).

2.24.8.2 Engineering/Technical

The Program Administrator has no information on technical developments beyond the period of performance of the EISG grant.

2.24.8.3 Legal/Contractual

The researchers have not applied for patents as a result of this project, but do hold patents on critical components.

2.24.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

Quality assurance plans should be developed as part of manufacturing plans to ensure quality product delivery. Further, installation and maintenance guides should be developed for use by field personnel to insure quality performance and safety. The solar thermal heat pump/chiller utilizes both ammonia and superheated water in its operation. Both are very dangerous and must be handled correctly to avoid injury to personnel or damage to nearby equipment. Ammonia can no longer be used in residential applications.

2.24.8.5 Production Readiness/Commercialization

The researchers should partner with a recognized provider of thermal equipment to understand market requirements and to take the results of this project to market.

2.25 Test Bed Design for Gas Turbine Exhaust Pressure Recovery

Awardee: Meruit, Inc.

Principal Investigator: Pete Fonda-Bonardi

2.25.1 Abstract

The object of this project, part of a multi-phase program, was to evaluate whether an annular recirculating diffuser could recover a useful amount of kinetic energy from the exhaust stream of a selected turbine, to design a test bed scaled to the turbine, and to get price quotes for its construction. The proposal set the energy to be recovered as 2 percent of the rated power of the turbine. The test bed was scaled to the selected turbine. The report presented a price quote for the test bed including the diffuser, instrumentation, fan/motor combination, test rig (structure), real estate, and staffing to build and test a scaled diffuser.

The researchers designed an annular recirculating diffuser to represent the future engine. Vendor firms supplied price quotes for the test bed structure, a fan/motor combination, instrumentation, the diffuser, and a yearlong test. The cheapest combination of these was $590,051. The recovered power, if the annular recirculating diffuser were fitted to the selected engine with no change to the spinning assembly, was calculated as 7,452 kW from the nominal 400 MW turbine, a 1.86 percent improvement. The researchers did not plan to take actual measurements in this project.

Keywords: Diffuser, efficiency improvement, energy recovery, gas turbines, exhaust cone, exhaust duct

2.25.2 Introduction

Currently gas turbines used for pipelines and for power generation exhaust hot gas either directly into the atmosphere (simple cycle) or into a heat-recovery unit (combined cycle) and thence into the atmosphere. Neither alternative recovers all the kinetic energy available from the massive flow and velocity (typically about Mach 0.5) of the exhaust stream.

All combustion turbines embody an exhaust diffuser of some design. The role of the exhaust diffuser is to convert kinetic energy in the gas flow to a pressure drop across the last turbine stage by slowing the gas flow in an expanding duct. Current designs are usually compromises between efficiency of the engine and the constraints of the engine installation. Most current designs sacrifice some efficiency to produce a more compact engine. However recovering this kinetic energy would make combustion turbines more efficient. The proposed annular recirculating diffuser could lower the exit pressure of the turbine, thereby increasing the pressure drop across the last stage of the turbine, allowing the turbine to extract more mechanical power from the same gas flow. The researchers estimated 2 percent of the rated power of the turbine could be recovered with an improved exhaust diffuser. An improvement of this magnitude is very significant for combustion turbines.

The researchers in this project proposed an improved exhaust diffuser design. The objective of this project was to prove the technical feasibility of the design using analytical techniques and to estimate the cost of testing the design in a later project. The cost estimate could be used as a basis for a detailed proposal for subsequent funding. Few details of the proposed designs were disclosed in the final report of this project.

2.25.3 Objectives

The goal of this project was to determine the recoverable kinetic energy in combustion turbine exhausts using an improved annual recirculating diffuser (ARD). It was one phase of a multi-phase program. The project objectives were as follows:

1. Obtain detailed flow profiles in the exit plane of the turbine wheel of a 5 MW turbine.
2. Compute the expected aerodynamics, the thermophysics, and the percent improvement, which must be over 2 percent to proceed.
3. Produce a complete set of diffuser component and assembly drawings.
4. Select a fan and motor combination capable of pulling the selected turbine's mass flow.
7. Produce a complete set of test rig component and assembly drawings.
8. Identify and bid all required instrumentation, logging computers, and software.
9. Determine total estimated cost of fabrication and testing of a completed ARD in a test bed.

10. Prepare proposals for hardware and testing in formats required by potential sponsors.
11. Perform ambient air hardware tests and measure recovered gas pressure.

2.25.4 Outcomes

The goal of this project was to design and demonstrate a test bed for the evaluation of kinetic energy recapture from the exhaust of combustion turbines. This project proceeded very differently than proposed for funding. The changes are noted below in each outcome:

1. The researchers obtained detailed predicted flow profiles in the exit plane of the last turbine wheel of a ~400 MW future turbine at 100 percent and 50 percent power from Siemens Power Generation. The flow data were from a much larger turbine than the originally proposed ~5MW turbine. The change occurred because the researchers were able to obtain data for the bigger turbine.
2. The researchers calculated the aerodynamics of the annular recirculating diffuser to permit mechanical design, price quotations, and efficiency calculations. The thermophysics calculations were not "complicated enough to warrant a separate task." The computed improvement proved very hard to assess. The researchers estimated recoverable energy at 3,726 kW in the full-flow case for the turbine, which is 0.932 percent and another 3,726 kW recovered in the diffuser, for a total improvement of 1.86 percent.
3. The researchers produced a set of component and assembly drawings for the annular recirculating diffuser scaled to the selected turbine. The lowest quote for fabrication of the outer diffuser was $55,250 and for the inner diffuser was $38,000.
4. Siemans Power Group researchers computed the airflow necessary for a scaled diffuser and estimated the air needed as 49,000 ACFM at 4” pressure. The researchers selected a fan/motor capable of 52,000 ACFM at 6” pressure. The lowest quote for the fan with variable inlet vanes was $21,500.
5. The researchers produced a set of component and assembly drawings of the test bed and received quotes for its fabrication from a large variety of vendors. With the lowest cost options, the test rig costs came to $157,000.
6. The researchers identified the make and type of all required instruments, logging computers, logging software, etc. They received two quotes for the instrumentation, one digital and one analog. The cheaper analog quote for 43 pressure taps and nine additional data channels was $7,650.
7. The researchers received quotes for the rental of a machine shop, utilities, and other costs. Rents and availability are changing quickly, but these costs were estimated at $63,300. Staffing costs were estimated at $287,000 for one year.
8. The researchers determined the total cost of fabrication and test of the completed ARD in the test bed. They estimated the overall cost of an ARD experiment to be $590,051 and to take one year.

9. The researchers did not complete ambient air hardware tests or measure recovered gas pressure. They reported that hardware tests will need further funding.

2.25.5 Conclusions

The results of this work are inconclusive with respect to the feasibility of using annular recirculating diffusers to capture significant additional kinetic energy from the exhaust of combustion turbines. The test bed design should provide the capability, with potential modification, to determine the amount of recovered energy. But until measurements are taken any estimates of efficiency improvements are speculative. The calculations leading to estimated recovered energy appear reasonable, but they are not directly transferable to smaller combustion turbines typically used in pipeline or distributed generation applications.

2.25.6 Recommendations

The researchers should consider modifying the test bed design to incorporate hot air/gas stream to replicate more closely the exhaust conditions exiting combustion turbines and determine materials requirements for the diffuser under hot gas exposure. They should complete measurements of the recovered kinetic energy to demonstrate improvements in efficiency. They should determine the recoverable energy across a range of combustion turbine sizes. Lastly, the researchers should work with the manufacturer of a combustion turbine to determine the market constraints on the length of any exhaust diffuser. Once that length has been determined, they should optimize the exhaust diffuser within those constraints.

2.25.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

1. Reduced environmental impacts of the California electricity supply, transmission, or distribution system
2. Increased public safety of the California electricity system
3. Increased reliability of the California electricity system
4. Increased affordability of electricity in California

The primary benefit to the ratepayer from this research would be increased affordability of energy in California through increased energy efficiency. While the researchers estimated the recoverable energy from combustion turbine exhaust, they did not confirm those estimates through demonstration tests. Therefore quantifying benefits to California would be premature and speculative.

2.25.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.25.8.1 Marketing/Connection to the Market

Siemens Power Generation, a large maker and marketer of combustion turbines, is cooperating in the redevelopment of this concept by providing crucial flow data for their combustion turbines. Continued interest on the part of Siemens or any other combustion turbine manufacturer will likely depend upon demonstrated test results.

2.25.8.2 Engineering/Technical

The researchers described their future development path. That path is to:

1. Build the ambient air test bed.
2. Prove the ARD works with ambient air.
3. Build a hot gas ARD and attach it to an as-built engine to prove it works with a hot engine.
4. Market the ARD to turbine OEMs.

The researchers estimate ambient air tests will require less than one year. They estimate the test bed and its component parts could be built in about three months. Testing might take an additional nine months. The scope of the hot turbine test depends on the turbine OEM partner.

2.25.8.3 Legal/Contractual

The researchers have applied for and have been issued patents: U.S. Patent #4,029,430 for the Radial Recirculating Diffuser and #5,603,605 for the Annular Recirculating Diffuser, the subject of this project.

2.25.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

There are no known environmental or safety risks associated with the concept design.

2.25.8.5 Production Readiness/Commercialization

The concept design is not ready for commercialization until proof of concept is demonstrated using actual live testing under ambient air conditions.

2.26 High Efficiency Heat and Power System for CCHP Applications

Awardee: Altex Technolgies Corp.

Principal Investigator: John Kelly

2.26.1 Abstract

Small combined cooling, heating, and power system costs are generally not cost competitive with utility supplied electric power and natural gas services due, in part, to their relatively low efficiency. This limits their deployment. The researchers in this project identified a high efficiency heat and power system concept that uses turbine cooling, heat exchanger, and working fluid innovations to increase power and overall efficiencies at lower cost. The design uses an ultralow NO_x emissions combustor technology to meet California Air Resources Board (CARB) 2007 emissions standards. The researchers showed the concept's power and overall efficiencies will reach 45 percent and over 80 percent respectively, at a cost 30 percent lower

than the cost of grid power. In addition, tests on a scaled combustor showed the combustor could meet emissions standards.

Keywords: Combined cooling, heat, and power; combined heat and power; high efficiency on-site generation; low emissions on site generation

2.26.2 Introduction

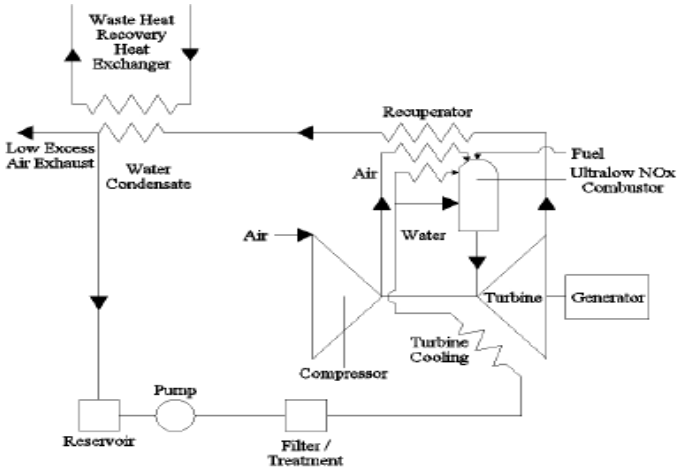
To effectively compete with grid power in an era of high natural gas prices, combined cooling, heat, and power systems must be very efficient and low in cost. This is particularly the case with small modular gas turbine power systems, where electric power generation efficiencies are currently only about 30 percent. These systems are at a disadvantage versus grid based large combined cycle gas turbines (CCGT) that can have efficiencies exceeding 50 percent and costs less than $1000/kWe.

To address this need, the research team identified and defined a high efficiency heat and power system (HEHPS) which uses turbine cooling, heat exchanger, and working fluid innovations that can raise small gas turbine combined cooling, heating, and power systems (CCHPS) power generation efficiencies to 45 percent. This approach works with the heat recovery system to create an overall fuel to energy conversion efficiency of over 80 percent. The high electric power and overall conversion efficiency could make the system competitive with the grid and drive HEHPS deployment in the California small applications market. The implementation of HEHPS could increase the efficient use of natural gas.

The focus of this work was to show the potential of an innovative approach to improve microturbine based combined heat and power system (CHPS) efficiency and specific power, while simultaneously meeting CARB 2007 emissions requirements, including the use of turbine cooling to allow higher turbine inlet temperatures.

Figure 28 presents an illustration of the high efficiency heat and power system (HEHPS) concept process. It uses a single shaft gas turbine that has a radial compressor and turbine.

Figure 28: HEHPS Process Diagram



2.26.3 Objectives

The goal of this project was to determine the feasibility of achieving high performance and low emissions using turbine cooling and other innovations in small combined heating, cooling, and power applications. The researchers established the following project objectives:

1. Analytically show that HEHPS could reach 45 percent electric power efficiency and 80 percent efficiency overall with 100 percent higher specific power.
2. Build and operate a sub-scale test facility that simulates gas combustor conditions for a 100kW system.
3. Design an instrument system to cover all important performance parameters.
4. Prove in sub-scale tests that the HEHPS ultralow NO_x combustor can achieve 2 ppm NO_x and 6 ppm CO at 15 percent O_2 dry, with good stability and a five-to-one turndown
5. Show analytically HEHPS emissions and efficiency can be reached in a full-scale system.
6. Show that lifetime costs are lower than grid power costs.

2.26.4 Outcomes

1. The researchers showed HEHPS can achieve 45 percent power efficiency, 80 percent efficiency overall and greater than 122 percent increase in specific power using GasTurb, an industry accepted model.
2. The researchers built a sub-scale test facility and ran tests that simulated the combustor residence times, temperatures, and mixing characteristics. The researchers operated the unit at nearly 69 kW thermal input at atmospheric pressure, simulating 276 kW thermal input for equal residence time at four atmospheres pressure characteristic of actual microturbine operation.
3. The researchers instrumented and calibrated the test system with accepted flow, temperature, pressure, and standard calibrated continuous emissions monitors.
4. The researchers showed the ultra-low NO_x combustor could meet CARB 2007 emissions standards at good stability. They measured combustor emissions of 2 ppm NO_x and 6 ppm CO with good flame stability over a four-to-one turndown.
5. The researchers' extrapolated performance of the test unit to full scale showed needed performance levels could be achieved
6. The researchers completed a cost analysis showing a HEHPS capital cost would be less than $1000/kWe. Compared to a grid power cost of $0.10/kWh, HEHPS could reduce power costs by 30 percent.

2.26.5 Conclusions

The sub-scale facility operated at conditions of temperature, residence time, and mixing that provided a reasonable simulation of the full-scale combustor operation at a capacity up to 82

kWe. As a result of gas supply limitations and pressure conditions, this capability was short of the 100 kWe simulation target.

Instrumentation operated as planned and yielded the needed results to quantify performance.

At steam fractions of interest, HEHPS combustor tests showed CO was less than 6 ppm at 15 percent O_2 dry and NO_x approached 2 ppm at 15 percent O_2 dry. Under the constrained conditions the test met CARB 2007 emission limits.

Measured test system performance indicated full-scale emissions performance needs can be met, subject to full-scale testing and verification.

Cost analysis that included both capital and operating costs indicated HEHPS lifetime costs are 30 percent lower than grid based power, assuming 10 cents/kwh grid price and $10/mmbtu gas price.

Based on test results and analysis, HEHPS can likely meet CARB 2007 emissions regulations for CCHP at performance (45 percent power and 80 percent overall efficiency) and cost levels 30 percent less than the grid. However, the researchers did not test the full turndown potential of the combustor. The researchers demonstrated process level feasibility of turbine cooling to improve combined heat and power performance.

2.26.6 Recommendations

Both temperature and pressure determine emissions. The researchers completed testing only under one atmosphere. They should complete testing under pressure (e.g., four atmospheres) to verify efficiency and emissions performance. As transient operation also affects efficiency and emissions performance, they should perform transient operation testing and validation.

The researchers should test and document performance under actual operating conditions of combustor pressure. On successful testing, the researchers should demonstrate full-scale performance under conditions that replicate load patterns of various applications (e.g., hotel/motel, corrections facilities, schools, and universities). They should undertake extended operation to validate durability of components, including under start/stop conditions.

The researchers should develop a commercialization plan and complete partnering agreements with micro-turbine manufacturers after patenting other aspects of the improvements that are part of the technology. They should begin development of operator/technician manuals and documentation.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.26.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

1. Reduced environmental impacts of the California electricity supply, transmission, or distribution system
2. Increased public safety of the California electricity system
3. Increased reliability of the California electricity system
4. Increased affordability of electricity in California
5. The primary benefit to the ratepayer from this research is increased affordability of energy in California.

HEHPS is a flexible concept that could be adapted to existing micro-turbine CCHP designs. By working with manufacturers, the HEHPS features could be adapted individually or jointly to achieve enhanced performance and lower cost. If the high performance HEHPS features are verified in full-scale testing, CCHP could be targeted for use in smaller applications throughout California. Commercialization of this concept would expand the use of local generation in micro-grids.

Public benefits for HEHPS could be substantial after ten years of deployment. Cost savings to the ratepayer could total $210 million/yr, with a fuel savings of 12.6million MMBtu/yr. In addition, environmental benefits could be substantial. Criteria pollutant reductions could be 445 tons/yr, with greenhouse gas emissions reduced 0.71 million tons/yr. These savings are based on the cost savings per kWh versus the grid, times the potential number of units (the total capacity could be 1266 MWe) that could be deployed.

2.26.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.26.8.1 Marketing/Connection to the Market

To commercialize the technology, the researchers will need to partner with a micro-turbine manufacturer. The researchers have held preliminary discussions with potential manufacturing partners.

2.26.8.2 Engineering/Technical

The researchers estimate technical completion may take three years and several million dollars. They plan to write an engineering specification for the concept.

2.26.8.3 Legal/Contractual

The ultra-low emissions combustor, an integral aspect of the technology, has been patented. According to the researchers, selected features of the concept are patentable, but applications have not been submitted.

2.26.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

There are no anticipated environmental or safety concerns. However the researchers must provide a basis for this declaration. Quality plans must be produced to ensure consistent performance.

2.26.8.5 Production Readiness/Commercialization

Production and commercialization readiness is premature until full-scale testing, including transient operation and fully pressurized conditions, is completed.

2.27 Highly Efficient Production of Electricity and Syngas Using a Natural Gas Fuel Cell

Awardee: Functional Coating Technology, LLC

Principal Investigator: Ilwon Kim

2.27.1 Abstract

This project demonstrated the potential viability of producing syngas (CO and H_2) and electricity using a novel chemical process called electrochemical partial oxidation (EPOx) integrated with a solid oxide fuel cell (SOFC). Previous efforts to integrate EPOx with SOFCs have yet to produce a stable, predictable supply of syngas. This project demonstrated a means to produce high electric power density and stable supply of syngas. Further work on scale up of this technology could result in practical use of EPOx technology in the production of synthetic chemical products and enhance the viability of SOFCs in the marketplace.

Partial oxidation (POx) chemical process has traditionally been used by industry to produce syngas for a variety of products/applications. EPOx is an innovative process that enables methane, natural gas, and biogas fuels to be partially oxidized in a SOFC configuration, thus producing syngas and electricity. The commercial viability of EPOx has been previously hampered by the instability of electrical power density and stable syngas generation rate. Researchers in this project were able to improve the stability and predictability of generation and composition of syngas from $EPOx$ so it could be tailored for specific synthetic products and integrated with a SOFC to cogenerate electricity.

The research team used a button cell in the lab to stabilize the generation and production of syngas with help of good catalyst performance and a barrier layer. Next the team demonstrated that injection of steam or CO_2 to methane feedstock enabled it to vary syngas composition (CO vs. H_2) depending on the specific synthetic products of interest (e.g., methanol, ethanol, lubricants, etc.).

Secondly, the researchers fabricated a module stack using a multi-cell (segmented in series) SOFC design to minimize the potential of carbon coking. The team also developed and tested a low cost ceramic manifold for easy gas collection along with the potential for scale-up.

The results of this work demonstrated the practical feasibility of producing syngas and electricity by integrating $EPOx$ with a SOFC. The recommended next step is to continue scale-up work with initial focus on portable power generators.

Keywords: Solid oxide fuel cells, natural gas, partial oxidation, electrochemical partial oxidation, syngas, biogas, Fischer-Tropsch process, methanol

2.27.2 Introduction

The development of more cost effective distributed energy resources (including fuel cells) and adoption of more energy efficient solutions in the marketplace are key California energy goals. This project was focused on the development of more efficient, cost effective energy solutions for industrial customers. Specifically, this work addressed the reformation of natural gas to syngas (mixture of H_2 and CO) for the downstream production of various synthetic chemicals including methanol (via the Fischer-Tropsch process) and other products.

Syngas is typically produced in the industry by a steam and partial oxidation (POx) reformation process using a combination of natural gas and air as feedstock. This technique works well on a small scale, but efficiency is relatively low and the syngas is typically diluted with nitrogen. A potentially more efficient, cost effective means to produce syngas from natural gas or biogas is the use of electrochemical partial oxidation (EPOx) coupled with a solid oxide fuel cell (SOFC). This integrated cogeneration concept produces syngas and generates electricity. The SOFC acts as an electrochemical reactor providing oxygen ions (O_2^-) that react with methane, the primary component of natural gas, at the anode. Under appropriate conditions SOFCs can produce both syngas (H_2 and CO) and electricity, as suggested by the equation below, giving rise to the term electrochemical partial oxidation (EPOx).

$$CH4 + O2- = CO + 2H2 + 2e- \qquad (-22 \text{ kJ at } 750^oC)$$

It is critical to produce a high, stable rate of syngas whose composition can be customized to produce various synthetic products for the EPOx/SOFC concept to be practical and cost effective. The research team achieved stable methane conversion and syngas production rates with the help of good catalyst performance and a barrier layer. The team also demonstrated that varying the H_2/CO ratio of the output syngas can be achieved simply by adding H_2O or CO_2 to methane feedstock, thus enabling tailored production of syngas (e.g., methanol, ethanol, lubricant, etc). This work also determined that a flattened, tubular EPOx design integrated in series with a multi-cell segmented in series (SIS) SOFC is the preferred integrated system package. Finally, the research team developed and fabricated a new ceramic manifold for the SIS SOFC using gel casting molds. This process, upon further development, has the potential to significantly lower the cost of manufacturing SOFC stacks and minimize gas leaks.

Previous work in this area has had limited success. Initial efforts exhibited relatively low power densities and thus low syngas production rates. More recently, higher rates of syngas production (20 SCCM/cm^2) along with higher electrical power density (0.7 W/cm^2) at 750°C have been demonstrated using conventional Ni-YSZ anode supported SOFC's.[87] In this case researchers reported stable SOFC electrical output for up to 300 hours, but they did not measure the chemical products versus time. Finally, the most recent work reported continuous degradation of methane conversion and syngas production rate during the first 30—40 hours of

87 Zhan, Z., Y. Lin, M. Pillai, I. Kim, and S. A. Barnett. 2006. *Journal of Power Sources* 161:460.

testing, even though the SOFC electrical performance was quite stable.[88] Adding a catalyst on the back of Ni-YSZ support in the fuel side reduced degradation. However the researchers did not achieve stable syngas generation during 100 hours of testing. The research team was able to demonstrate both high power density and higher rates of stable syngas production that could result in practical use of the EPOx concept.

From a customer point of view, EPOx is viewed as a syngas generator with electricity as a by-product. The generation of electricity on site gives EPOx a unique advantage over conventional POx syngas generators from a source efficiency and economic perspective. Electric generating efficiency of SOFCs are typically in the range of 40—45 percent compared to typical grid power source efficiency of 35—40 percent, not including the impact of grid power losses. Electricity produced on site can be used to offset electricity consumption at the customer facility and lower overall operating costs. The generation of electricity does lower syngas production. However, overall economics supports this trade-off, since electricity is typically a more costly and more valuable form of energy compared to syngas.

From a SOFC vendor point of view, EPOx can be described as a SOFC power plant that generates syngas as a byproduct for a total system energy efficiency of 85—90 percent. The additional revenue from producing syngas as a byproduct can help further improve the economics of SOFCs in the marketplace for certain industrial customers that use syngas to produce synthetic products such as methanol.

In addition, integrating EPOx with SOFCs could provide SOFC manufacturers with an opportunity to improve net electrical and overall fuel efficiency and better thermal management of the stack compared to conventional SOFCs. There are two reasons for this: SOFC essentially operates under low fuel utilization condition in the EPOx process so that stack performance is not limited by fuel side concentration polarization, and the EPOx process is slightly exothermic as compared to the highly exothermic conventional SOFC process.

An integrated EPOx/SOFC could also be used by non-industrial customers to produce a liquid fuel like methanol. Liquid fuels could easily be stored, transported, and used as fuel to produce electricity during peak market conditions. This concept could offer advantages in certain market conditions compared to conventional sources of peaking power such as natural gas. The natural gas market is somewhat fragmented and at times subject to large price swings depending on regional, seasonal, and global conditions.

Finally, the market value of chemicals produced from syngas such as methanol (Fischer-Tropsch) and synthetic lubricants which retail at $5/pint could make EPOx a very attractive product for industrial customers.

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88 Pillai, M. R., D. M. Bierschenk, and S. A. Barnett. 2008. "Electrochemical Partial Oxidation of Methane in Solid Oxide Fuel Cells: Effect of Anode Reforming Activity," *Journal of Power Sources.*

2.27.3 Objectives

The goal of this project was to demonstrate a more practical, cost effective means to reform natural gas to syngas (mixture of H_2 and CO) for the downstream production of various synthetic chemicals such as methanol, ethanol, and industrial lubricants. The researchers established the following project objectives:

1. Demonstrate high electrical power density (> 0.6W/cm2) and high syngas generation rate (>20 SCCM/cm2) under methane fuel.
2. Explore conditions for thermally self-sufficient operation as well as high performance.
3. Assess the thermal gradient across the segmented in-series module.
4. Demonstrate low leak fuel feeds using the gas manifolds.
5. Demonstrate a stable performance with drops in power density and syngas generation rate less than 5 percent during 1000 hours of operation.
6. Demonstrate use of fuel feed mix of simulating composition of natural gas for stability against coking.
7. Fabricate module stack and demonstrate total output power >~ 40w and total syngas generation rate > than 1 liter /min using the multiple modules stack.
8. Vary the output syngas composition by adding steam or CO_2 to ultimately control composition for downstream processes.
9. Assess the effect of addition of H_2S to the fuel stream. H_2S is a contaminant found in natural gas which is detrimental to conventional solid oxide fuel cell anodes.

2.27.4 Outcomes

1. The researchers obtained maximum power density (~0.9W/cm2) and a high syngas generation rate (~30 SCCM/cm2) under methane fuel at 800°C, exceeding performance targets.
2. Researchers demonstrated a thermally self-sufficient condition with high power density with a high syngas conversion rate with cell voltage ~ 0.4V and O2- /CH4 ratio ~ 1.2.
3. Researchers observed no appreciable thermal gradient over the segmented in series (SIS) solid oxide fuel cell (SOFC) module greater than the error range of the pyrometers (5—10°C).
4. The researchers used gel casting methods to develop partially stabilized zirconia based gas manifolds for the SIS SOFC module. They used glass based hermetic seals to achieve leak tight manifolds and SOFC manifold components. They detected no appreciable leakage for testing over 100 hours with hydrogen flowing at 800°C.
5. The researchers used the combination of an inert barrier layer and a coke free Rh based catalyst for button cells that achieved a stable syngas generation rate under testing

performed for >140 hours using methane as the fuel. Fuel cell testing was interrupted after 140 hours due to a power outage resulting from severe weather. The testing computer and cell were damaged due to the incident, and longer testing could not be performed for the remainder of the project.

6. The researchers demonstrated high power density (0.6W/cm2) and stable syngas operation for the SIS module tested under internal partial oxidation of iso-octane. They selected iso-octane as the upper limit of high hydrocarbon components found in natural gas. This result demonstrated the stability against coking for using natural gas in the most stringent test conditions and provided stronger demonstration of stability against coking than the test which simulated the use of natural gas.
7. The researchers successfully developed all techniques necessary for fabricating the stack. However fabrication of the actual fuel stack could not be completed due to lack of time and funds. Researchers scaled up SIS SOFC modules and successfully developed a low cost ceramic interconnect. The interconnect material needed to be changed due to problems associated with the materials purchased. Nonetheless, the successful development of a low cost interconnect marks an important milestone for commercialization of SIS SOFC modules.
8. The addition of 20 percent steam to the methane fuel increased the H_2/CO ration to 1.9. This is slightly lower than the ideal ratio of 2.1 needed for methanol production. The addition of 33 percent CO_2 to the methane gas achieved a H_2/CO ratio of 1.2, which is optimal for the Fischer-Tropsch process for synthetic fuel and chemicals. The researchers obtained relatively high power density of ~0.8W/cm2 and stable electrical performance under 70 hour tests. Optimization of reforming catalysts could provide even more precise control of syngas composition (CO vs. H_2) for specific synthetic products.
9. The button cell exhibited stable SOFC operation using hydrogen fuel along with 100 ppm H_2S.

2.27.5 Conclusions

The researchers demonstrated the feasibility of developing a more practical, cost effective means of reforming natural gas to syngas for the downstream production of various synthetic chemicals. Although they demonstrated promising technical feasibility, the team was not able to complete its work in developing an EPOx/SOFC concept that is reliable and cost effective over long periods of time under various cyclic heating conditions. It is still not clear that co-generation of syngas and electricity makes sense when compared with other concepts, such as ion transport membrane technology under development by industrial gas suppliers. Considerable development is needed to further prove the concept can be scaled up and practical for use by industry.

2.27.6 Recommendations

The researchers should ensure that this concept can compete favorably against similar development efforts under way by completing the module stack fabrication and successfully testing it under methane or simulated natural gas for durability and reliability under various

cyclic heating conditions. The team should also scale up the concept, optimize catalysts for various synthetic products, and develop a cost effective single step firing process that could enable practical manufacturing. Finally, the team should optimize the performance of an integrated SIS SOFC system for different hydrocarbon fuel stocks.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.27.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

1. Reduced environmental impacts of the California electricity supply, transmission, or distribution system
2. Increased public safety of the California electricity system
3. Increased reliability of the California electricity system
4. Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of energy in California. In 2006 California consumers spent $19 billion for natural gas, of which 43 percent was for electricity generation and 23 percent for industrial applications. Assuming 10 percent market penetration of distributed electrical power generation using EPOx, California's chemical industry has a potential benefit of approximately $200 million per year from lower electricity costs and profits from sales of incremental synthetic fuels.

2.27.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.27.8.1 Marketing/Connection to the Market

This concept is not yet sufficiently developed to pursue market connections. The researchers have formulated a detailed plan for SIS SOFC manufacturing process development. If successful, it could dramatically lower the manufacturing cost and ultimately make large scale production feasible. The initial market target is small portable power generator applications. The team has continued efforts to commercialize its SOFC module stack which is the core part of the power generation system. The targeted customer is the system integrator. Researchers are

interested in either directly selling the stack or co-producing the stack with a system integrator in a joint venture.

2.27.8.2 Engineering/Technical

The research team is investigating similar work by others in the industry to further explore collaboration opportunities.

2.27.8.3 Legal/Contractual

The research team has applied for a U.S. patent application number 11/341,807 and is waiting for a judgment from the patent office. The scope of the patent covers the design and process of producing SOFCs based on EPOx.

2.27.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

There are several technology related risks associated with this concept, including successful optimization of catalysts for precise control of syngas composition, scale up of the concept, system reliability, durability, and competitive manufacturing costs.

2.27.8.5 Production Readiness/Commercialization

This concept/technology is not ready for commercialization.

2.28 Feasibility Assesment of Operating Gas Engines on Alternative Gas Fuels

Awardee: Colorado State University

Principal Investigator: Dan Olsen

2.28.1 Abstract

California has abundant supplies of alternative fuel stocks that could be used as supplements to natural gas for electricity generation. Using these indigenous supplies could reduce dependence on traditional fuels while processing reactive gases that might otherwise be leaking into the atmosphere or flared with no energy benefit. An important characteristic of an alternative gas supply for use in an internal combustion engine is its knock characteristic or methane number. The limited published availability of this parameter hinders design of engines for high efficiency and low emission operation. This project developed and used an innovative fuel blending system and modified test engine to determine methane numbers for eight samples of alternative gaseous fuels. The results were highly repeatable and ranged from a low of 24 for coal gas to 140 for landfill gas. Comparison of these results with existing model based methods focused primarily on methane confirmed that this direct measurement provides more accurate results across a broad range of fuel mixes containing components such as hydrogen and carbon monoxide.

Keywords: Methane number, knock, alternative fuels, gaseous fuels, CFR Engine, fuel blending system

2.28.2 Introduction

Development of cost effective alternative gaseous fuels for electricity generation faces technical challenges. Questions of reliability and ability to meet California air quality standards also hinder development and commercialization of these fuels. One key to overcoming these barriers would be a readily available and accurate method for determining an alternative gas supply's knock characteristics. This would allow commercial installations to fine-tune engine design and operations to improve efficiency and help ensure reliable, environmentally compliant operation. The researchers proposed to develop a method for directly measuring the knock characteristics of a wide range of test gases employing a unique gas blending apparatus and a modified test engine. The test apparatus evaluated gas samples representative of reformed natural gas, coal gas, wood gas, digester gas, and landfill gas.

2.28.3 Objectives

The goal of this project was to determine the feasibility of directly measuring the methane number for various alternative gaseous fuels and to assess the ability of current methane number models to predict the methane number for the gaseous fuels tested. The researchers established the following project objectives:

1. Demonstrate ability to create various alternative fuel blends with a new blending system.
2. Run an engine on natural gas and measure the methane number. Demonstrate 95 percent confidence interval of +/- 1.5 percent or less for methane number measurement.
3. Complete methane number test matrix.
4. Assess common gas engines that will operate on different alternative gas fuels.
2. Compare measured methane numbers to calculated values using currently available calculation models.[89]

2.28.4 Outcomes

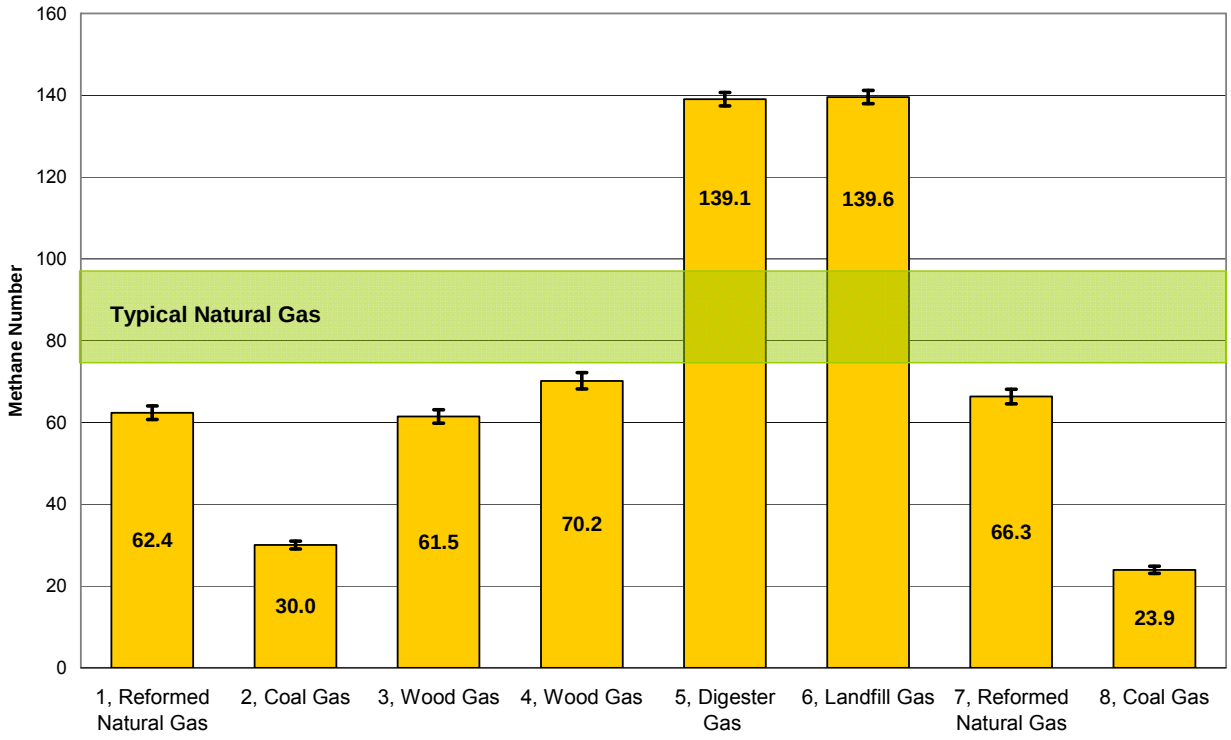
1. The researchers developed and used a computer controlled gas blending system as planned. The system was capable of blending hydrogen and methane to yield methane numbers from zero to 100 as well as beyond 100 by including carbon dioxide in the mix. The computer determined the required quantity of each component in the mixture under test. The researchers used a gas chromatograph to verify gas composition ensuring quality of results.
2. Researchers adapted a 1957 Cooperative Fuel Research F-2 engine for the project. The F-2 is a spark ignited single cylinder, four stroke engine whose cylinder assembly allows the compression ratio to be changed while it is running. Converting the engine to gaseous fuels included use of a computer controlled air fuel ratio controller to ensure

89 This was not an explicitly numbered goal in the final report, but was included in the grant application, and results were presented in the final report.

precise air fuel ratio control. The researchers took 10 methane number measurements for each gas test blend to assess repeatability. They determined a 95 percent confidence interval. The project's overall 0.36 percent result was below the targeted +/- 1.5 percent.

3. The researchers tested each test gas three times to determine its methane number. This was done by determining the blend of reference gas that yielded the same knock as measured when running the test gas. The methane number was the percentage of methane in the reference gas. Results are shown in Figure 29 below.

Figure 29: Methane Number Results for Blended Fuels



4. The researchers varied the compression ratio while running each test gas to a point where light audible knock began. The resulting data supported the expected conclusion that there would be a linear relationship between higher methane numbers and higher compression ratios at the knock point.

5. The researchers compared three existing theoretical models intended to calculate methane number for various natural gas compositions to the results obtained in this research. The models tested were the AVL (Institute for Internal Combustion Engines, Austria), the GRI (Gas Research Institute), and the WKI (Waukesha Knock Index). Since none of the models was designed to operate with all (or any in some cases) of the gas

compositions tested, none gave accurate results for the entire field of test gases. The AVL model offered the best results, correlating well with six of the eight gases.

2.28.5 Conclusions

The research successfully demonstrated the feasibility of using a test engine to determine methane numbers for a wide range of alternative gaseous fuels potentially available for use in internal combustion engines. At present the wide range of possible gas compositions has not made it possible for a single computational model to make this determination. This can lead to sub-optimal engine applications in the field. The method demonstrated in this research can be used to make these determinations and would also be a highly desirable benchmarking protocol for development of simpler and more accurate methane number modeling techniques.

The gas blending and control apparatus performed well. Inclusion of gas chromatograph testing of the blended samples during testing ensured high quality and repeatable test results.

Upgrading and converting the test engine to use gaseous fuels was successful and led to valid, repeatable results. The quality of this research was reflected in choices such as replacing the ignition system with a more modern electronic unit, adding a dehumidifier to the inlet air intake to conform to ASTM guidelines for similar testing, and use of a custom specified air fuel ratio controller.

The wide range of methane numbers among the test gases reflected their varying compositions of gases other than methane. In particular, variations in hydrogen, nitrogen, carbon dioxide, and carbon monoxide were causal factors during testing.

The expected variation in knock tendency among the test gases confirmed the benefit of having an accurate methane number for the gas intended for use in a given engine being manufactured for a commercial application. The data presented illustrated how easily a 10 percent loss in efficiency can occur through a mismatch of engine design and methane numbers among the test gases.

A model capable of accurately determining methane number of a gas targeted for a particular commercial application could be a simpler approach than the laboratory testing in this research. Given the importance of this determination and the apparent lack of models applicable to a wide range of potential gases, further research and development of such models is important. The laboratory test developed in this research could provide an important benchmark for use in this work.

2.28.6 Recommendations

Given the high quality of this research, it appears this team would be well qualified to undertake further development and refinement of methane models. Using the laboratory approach from this research or models as they are developed, a project to characterize typical methane numbers for various field gases could be useful to the engine design and manufacturing community. The Program Administrator recommends that the researchers talk to engine manufacturers and discuss the manufacturers' needs for alternate fuels data. In

addition to data needs, the manufacturers might indicate which fuels they would support in future products. Information of this type would lead to more focused research.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.28.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

1. Reduced environmental impacts of the California electricity supply, transmission, or distribution system
2. Increased public safety of the California electricity system
3. Increased reliability of the California electricity system
4. Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of energy in California. The State has abundant sources of alternative fuel gases with potential for use in engines generating electricity. Better data on these gases' methane numbers would help achieve maximum efficiency through tailored engine design, reducing overall costs of production. The efficiency improvement could be as much as 10 percent based on the data from this project. Overall savings would be proportional to the amount of electric production utilizing alternative fuels.

2.28.8 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.28.8.1 Marketing/Connection to the Market

This approach to determining precise methane numbers has potential as an alternative to existing model based calculations. It is unclear whether individual manufacturers would set up their own test engines or rely on an outside laboratory to offer this service.

2.28.8.2 Engineering/Technical

The most significant technical development subsequent to the research was completion of a master's thesis and publication of several technical papers describing the project.

2.28.8.3 Legal/Contractual

The researchers have not applied for patents.

2.28.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

None were identified.

2.28.8.5 Production Readiness/Commercialization

See comment under Marketing/Connection to the Market

2.29 A Pore Flow Reactor for Landfill Gas Clean-Up

Awardee: University of Southern California

Principal Investigator: Theodore Tsotsis

2.29.1 Abstract

This research project demonstrated the feasibility of using a catalytic pore flow reactor to remove toxic components typically found in landfill gas. Successful removal of such contaminants could increase the utilization of landfill gas for electric production or other applications in lieu of flaring or allowing escape into the atmosphere.

The researchers successfully deposited a platinum nano-catalyst on membranes designed to function in pore flow mode. Researchers used the membranes to treat a simulated landfill gas containing six representative non-methane organic compounds in a typical mix of methane, oxygen, nitrogen, and carbon dioxide. They demonstrated complete destruction of these compounds at temperatures ranging from 200° to 290° Celsius.

The researchers provided preliminary estimates of the cost/volume of treated gas and a detailed proposal for further work toward commercialization.

Keywords: Landfill gas, pore flow reactor, catalyst, nano-catalyst

2.29.2 Introduction

California's landfills represent a significant source of methane for use in electric production or as pipeline gas. Much of the gas from these sources contains traces of various organic compounds other than methane that may contain halogens and sulfur. Unless removed, these corrosive compounds present barriers to complete an economic recovery of this potential resource and pose a threat to the environment. Power production capital and operating costs are increased and neither power production nor flaring completely avoids discharge of harmful compounds such as hydrogen chloride into the environment.

If an economic method for completely removing non-methane organic compounds (NMOC) from landfill gas could be developed, California ratepayers would benefit from increased supply of fuel for power production or other pipeline uses. Reduced emissions from landfills due to gas recovery and removal of NMOC would benefit air quality.

The researchers proposed to demonstrate a method of removing contaminants through catalytic oxidation in a pore flow reactor (PFR). The reactor consisted of porous ceramic membranes with

a thin film of nano-catalyst deposited on the surface of the pores. Forcing all NMOC through the pores and bringing them into direct contact with the catalyst surface ensured full oxidation. A key to success was maintaining flow through the membrane in the Knudsen flow regime (KFR), wherein collisions with the catalyst laden pore walls prevail over gas-gas collisions. Knudsen flow occurs where the membrane pore size is of the same or smaller order of magnitude as the mean free path. While both the PFR concept and potential for nano-catalysts to remove contaminants are well known, the combination of both represents a novel and potentially highly effective approach for cleanup of landfill or other gas sources.

2.29.3 Objectives

The goal of this project was to study the pore flow reactor concept and to demonstrate its feasibility for removing NMOC typically found in landfill gas. The researchers established the following project objectives:

1. Deposit nano-catalysts on test membranes and characterize their properties such as catalyst loading, particle size, and surface area.
2. Investigate the catalytic properties of prepared membranes using simulated landfill gas. Investigate parameters such as temperature, space time, water composition, and need for additional oxygen. Prove that membranes function stably without unwanted by-products.
3. Test membranes further in the pore flow configuration under a transmembrane pressure. Compare the conversion and yield with those in conventional reactors.
4. Calculate capital and operating costs.

2.29.4 Outcomes

1. Nano-catalysts were deposited on the membranes, and the researchers characterized their properties with respect to catalyst loading, particle size, and active surface area. After literature review, the researchers selected a platinum based catalyst and two or three layer porous ceramic membranes supplied by industrial partner M&P. Optimization studies led to design and fabrication of membranes yielding higher percentage Knudsen flow for each average pore size.
2. The researchers investigated the catalytic properties of the membranes in conventional mode (permeate side closed) using simulated landfill gas. The membranes functioned appropriately without unwanted byproducts. No additional oxygen was needed.
3. The researchers tested the membranes in the pore flow reactor configuration under a transmembrane pressure. They conducted long duration studies to test the reactor's ability to operate in a stable manner and to destroy completely the targeted compounds in the simulated landfill gas. Results were very successful, with complete destruction for all six contaminants at temperatures ranging from 200° to 290° Celsius. Principle by-products of the reaction were mineral acids (e.g., HCl, HF) for which conventional adsorbents exist. Figures 30 and 31 show results of typical runs for two targeted components, with each point representing at least 12 hours of on-line operation.

Figure 30: Pore Flow Reactor Conversion of Dimethyl Sulfide

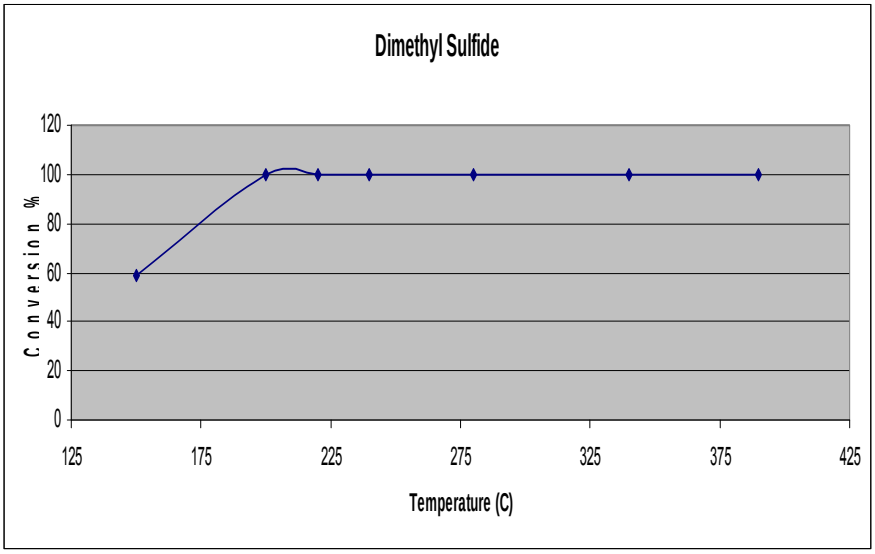
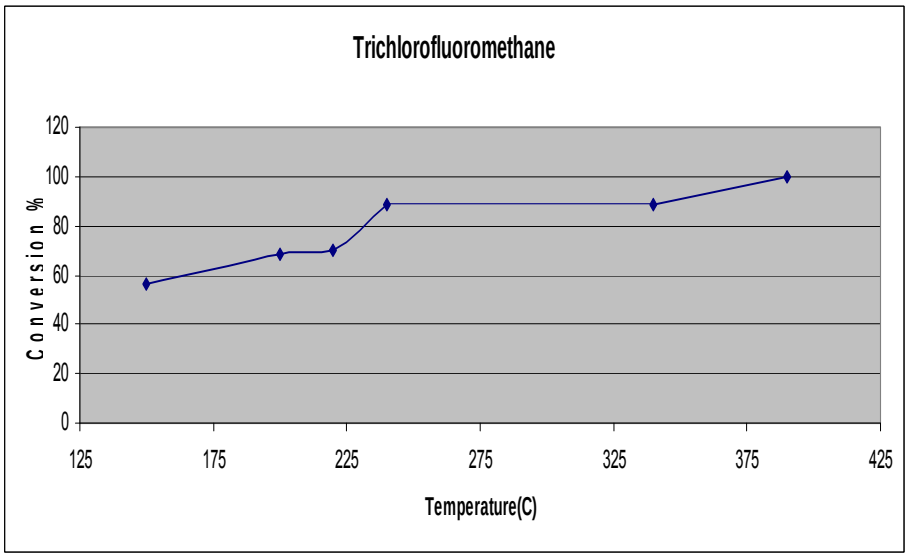


Figure 31: Pore Reactor Conversion of Trichlorofluoro Methane



4. Researchers performed preliminary economic analysis in collaboration with industrial partner M&P and commercialization partner GCE to assess economic incentives for using the technology. Using the results from this research, the researchers estimated treatment of one cubic foot per minute of the simulated landfill gas would require 0.2093 square meters of treated membrane, which M&P estimated would cost $1,000 to $1,500 per square meter. Scaling up for a typical 2,000 cubic foot/minute landfill production facility would yield capital costs of $837,200. More detailed payback calculations would include balancing this cost against savings in original material specifications (avoiding use of less costly specialty materials to resist the corrosive contaminants) and reduced

operating downtime for maintenance. The researchers indicated such study was underway in collaboration with GCE after this project ended.

2.29.5 Conclusions

The researchers successfully demonstrated use of nano-catalysts in a pore flow reactor to achieve complete cleanup of NMOC in simulated landfill gas. The Final Report provides detailed narratives for the design, construction, and testing of the pore flow reactor as well as a comprehensive background on other approaches to removal of NMOC and an extensive list of relevant reference materials.

The information presented in the Final Report supports successful operation of the pore flow reactor. However there is no corresponding data for a conventional reactor. Thus it is not possible to determine if the pore flow approach is superior to a conventional membrane using a similar catalyst.

2.29.6 Recommendations

This research was very promising and has high potential for successful development as a commercial application. The comprehensive Final Report narrative and the researchers' and associated partners' extensive experience provides a valuable starting point for further research and development, including:

1. Conduct more detailed side-by-side testing of the pore flow reactor against a comparable conventional design to explore costs and benefits of the pore flow approach.
2. Test the reactor with a broader range of NMOC compounds, including the presence of siloxanes.
3. Investigate formulations less expensive than noble metal catalysts.
4. Perform long term field testing of the reactor at an actual landfill gas source.

The discussion of projected capital and operating costs was of necessity very preliminary at this stage of research. As further research more clearly defines the path towards a commercial scale reactor, costs and benefits can be assessed for application to landfill gas or other industrial cleanup applications

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.29.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

1. Reduced environmental impacts of the California electricity supply, transmission, or distribution system
2. Increased public safety of the California electricity system
3. Increased reliability of the California electricity system
4. Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is the potential to reduce environmental impacts of the California energy supply and distribution system. If successfully scaled to commercial size, the reactor could remove NMOC from currently utilized and potential additional landfill gas supplies. This could reduce capital and operating costs and potential discharge of toxic compounds from current energy production and flaring sites and pave the way for economic recovery and utilization of presently unused landfill gas. The researchers' close collaboration with proven industrial and commercialization partners increases the likelihood of a successful transition to commercial operation.

2.29.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.29.8.1 Marketing/Connection to the Market

There appear to be no competing technologies available with the same potential for complete NMOC removal from landfill or similar gases. Traditional adsorption/absorption approaches currently in use only transfer NMOC from the gas to another medium, leaving their ultimate disposal unaddressed. The researchers are working with industrial partners to go to market.

2.29.8.2 Engineering/Technical

Field testing will provide important insights into the potential for commercial success. The researchers believe that long term testing is a key to market acceptance.

2.29.8.3 Legal/Contractual

The researchers indicated they have not applied for patents, and there were no apparent conflicts with existing patents.

2.29.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

There appear to be no environmental or safety concerns with moving forward to a field test. As that test progresses the researchers plan to answer the environmental, safety, risk and quality issues.

2.29.8.5 Production Readiness/Commercialization

While the researchers estimated a somewhat lengthy (5—10 year) path to a commercial launch, continued research funding and degree of fit with emerging greenhouse gas goals and legislation could significantly accelerate progress.

2.30 Enabling the Thermochemical Production of Hydrogen from Water: Investigation of the Bunsen Reaction in a Low Vapor Pressure Solvent

Awardee: Oregon State University

Principal Investigator: Alexandre Yokochi

2.30.1 Abstract

This project tested the feasibility of producing hydrogen for fuel by use of a simplified thermochemical cycle using the Bunsen reaction in an ionic liquid. The intention was to decrease the water processing requirements and thermochemically produce hydrogen at lower temperatures. Researchers designed and fabricated a test reactor and conducted experiments in the system. They observed fast kinetics for the Bunsen reaction, but found subsequent generation of hydrogen iodide and sulfuric acid gas streams appropriate for high temperature processing difficult. This difficulty stemmed in part from the high acidity of the hydrogen iodide product. The extreme acidity of the material, coupled with the presence of excess water in the reaction, led to hydrolysis of the intermediate products. Reactions also led to the formation of hydrogen sulfide.

Taking advantage of the production of hydrogen sulfide in the product stream rather than hydrogen iodide suggests that a new cycle could be created and should be investigated. Alternatively, carrying out the hybrid cycle in ionic liquids may be an alternate strategy that avoids carrying out the reaction in an aqueous stream while generating a hydrogen iodide gas stream.

Keywords: Thermochemical hydrogen production, Bunsen reaction, ionic liquid, sulfur iodine cycle, sulfur-sulfur cycle

2.30.2 Introduction

The production of clean burning and renewable hydrogen is an important California energy policy. Currently hydrogen is manufactured primarily from steam reforming of natural gas or electrolysis of water.

A potentially more efficient way to produce hydrogen fuel using a renewable energy source is high temperature thermochemical decomposition of water using solar heat. Efficiency of the process (primary heat to hydrogen) could improve to over 50 percent with direct thermochemical production from about 25 percent with electrolysis. The commercial success of large scale thermal decomposition of water into molecular hydrogen and oxygen is based on reducing the necessary temperature of >2000˚C for direct thermolysis of water to temperatures below 1000˚C, a temperature that can be achieved in solar thermal power plants. Brown and coworkers conducted a review of 25 suggested thermochemical cycles,[90] from which they

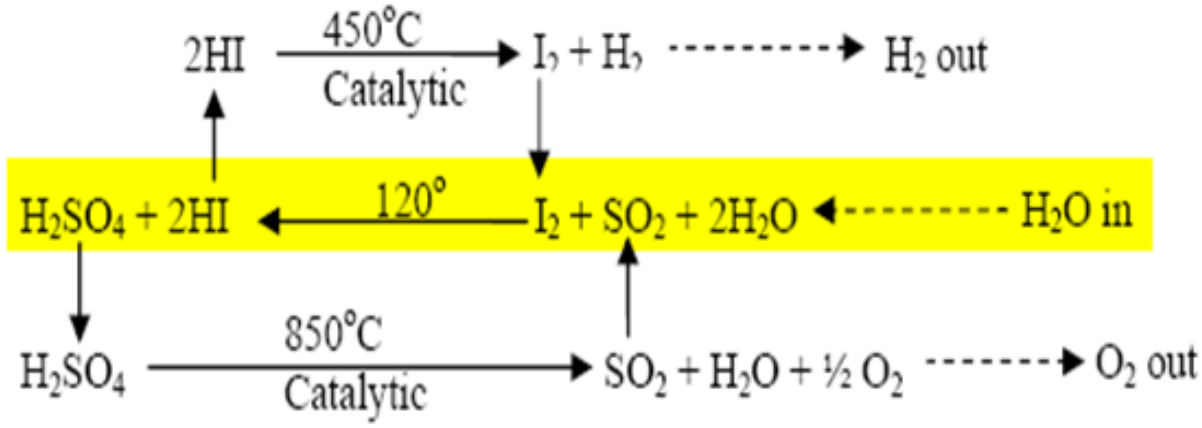
90 L.C. Brown, et al. "High Efficiency Generation of Hydrogen Fuels Using Nuclear Power," Final technical report for the period Aug. 1, 1999 through Sep. 30, 2002, SF21888, *General Atomics Corp. Report* GA-A24285 (June 2003).

selected two cycles as the most promising. The first was the three step Sulfur-Iodine (S-I) cycle described by Besenbruch[91] (Figure 32) and the second was the four step Adiabatic UT-3 cycle described by Yoshida.[92]

The goal of this project was to perform research leading to an alternative process to produce thermochemical hydrogen from water. The approach was to develop a technology compatible with the abundant solar thermal resource available in much of California and capable of being installed on a local scale (i.e. on a scale capable of supporting a small township). Researchers investigated the concept of carrying out the Bunsen reaction, one of the crucial steps requiring improvement to enable practical implementation, in ionic liquids. The advantage conferred by

the use of ionic liquids results from their low vapor pressures and suitability to carry out chemical reactions.

Figure 32: The Sulfur-Iodine Reaction for the Production of Hydrogen from Water



2.30.3 Objectives

The goal of this project was to determine the feasibility of thermochemically producing hydrogen from water using the sulfur iodine reaction. The researchers established the following project objectives:

1. Design a system able to react SO_2 with H_2O in low vapor pressure medium. Include capability to properly control the reaction mixture temperature from -20 to 150° C, the ratio of SO_2 to H_2O, the flow rate of SO_2 and H_2O through the system up to 50 Standard Cubic Centimeters per Minute (SCCM), and the concentration of halogen (I_2 or Br_2) in

91 G.E.Besenbruch, "General Atomics Sulphur-Iodine Thermochemical Water-Splitting Process," *American Chemical Society*, Prepr. 271, 48-53 (1982).

92 H.Yoshida, et al., "A Simulation Study of the UT-3 Thermochemical Hydrogen Production Process," *International Journal of Hydrogen Energy*, 15, 171 (1990).

mixture. Include the capability to analyze effluent gases for SO_2, SO_3, H_2O, I_2 (or Br_2) and HI (or HBr) by gas chromatography.

2. Control gas flow rate and reactor temperature from control system and acquire data on gas chromatograph in real time.

3. Demonstrate that over 50 percent of the SO_2 fed into the test reactor will be converted to SO_3 by monitoring the concentration of HI in the effluent gas.

4. Produce HI (or HBr) gas stream with flow rate up to 20 SCCM with less than 1000 ppmv H_2SO_4/SO_3 present.

2. Produce H_2SO_4/SO_3 gas stream with flow rate up to 20 SCCM with less than 1000 ppmv HI (or HBr) present.

2.30.4 Outcomes

1. The researchers designed and constructed an aluminum reactor vessel with ports for the reactant gas feeds, product stream exhaust, thermocouple instrumentation, and a septum for charging the reactor with a stock solution of the halogen in ionic liquid. The reactor was equipped with temperature control equipment, and the outlet was attached directly to a gas chromatograph. The researchers used this system for subsequent experiments.

2. The researchers equipped the reactor with a proportional controlled heater, controlled the feed gas streams using mass flow controllers, and directly connected the reactor's effluent to an SRI8610C gas chromatograph. The researchers measured the effluent gas in real time, but collection of a gas chromatogram sample typically requires several minutes. In the course of the work the researchers added an ultraviolet visible immersion probe to monitor concentration of the remaining halogen. This is a more rapid method for measuring the reaction completeness.

3. The researchers monitored the reaction of SO_2 by gas chromatographic measurement of the gas composition of the effluent gas. SO_2 concentration in the effluent stream was immediately greatly decreased due to the high solubility of SO_2 into the ionic liquids tested. However no HI was present. Researchers instead carried out the proof of concept test by using a colorimeter to monitor I_2 concentration decrease in the reaction mixture. The researchers observed rapid reaction with strong temperature dependence. When SO_2 was present as the limiting reagent, 100 percent of this reactant was consumed in the reactor.

4. The researchers completed a parametric exploration of the reactor's ability to produce hydrogen iodide. The main parameters explored were reaction temperature, water concentration, SO_2 concentration, and I_2 concentration. The researchers evaluated the issue of low production rate of HI despite high SO_2 conversion. In most ionic liquids they measured only trace amounts of hydrogen iodide, and they found hydrogen sulfide and hydrogen fluoride were also formed. They identified the problem as caused by strong acidity of HI, which reacted with ionic liquid constituents and caused hydrolysis

of the BF_4- ions. This led to the formation of HF gas. The researchers expected that since HPF_6 is a much stronger acid than HI, HI would be generated from the reaction. However they observed low evolution of HI gas along with PF_6- ion hydrolysis. The researchers found that employing 1-butyl-3- methylimidazolium triflate led to a system from which it was possible to increase production of gaseous HI and eliminate the formation of HF in the effluent gas. However the temperature range available in the reactor could not meet the target levels of HI generation.

5. The researchers found that carrying out the reaction in a 1-hexyl-3-methylimidazolium hydrogensulfate based ionic liquid and heating the ionic liquid to 160° C led to rapid evolution of a compound identified as H_2SO_4/SO_3 through the gas chromatograph.

2.30.5 Conclusions

The researchers demonstrated it is feasible to produce hydrogen thermochemically using ionic liquids and various halogen pairs. Although they demonstrated technical feasibility, they did not demonstrate practical feasibility. Considerable development efforts remain, and it is possible that reaction pairs other than those investigated here will prove more practical.

2.30.6 Recommendations

The researchers should investigate, beyond literature review, ionic liquid compositions from which hydrogen iodide gas and/or other hydrogen halogens can be readily elutriated without decomposition of the ionic liquid. The researchers should also examine the feasibility of other thermochemical cycles, such as sulfur-sulfur. The present work demonstrated evolution of H_2S from the reaction product stream and also demonstrated evolution of the H_2SO_4/SO_3 stream. The problem remaining is to evaluate whether hydrogen sulfide can be efficiently converted to SO_2 by water or whether only thermal cracking of the H_2S (to produce elemental sulfur) will occur. Future research also needs extensive work on the development of suitable catalysts. Such catalysts would need long term testing to determine activity degradation in the presence of sulfur and other chemicals. The researchers should investigate thermal cycling, from cold to hot and back, of equipment and reactions to determine applicability to solar thermal cycles. They should also investigate the need for thermal energy storage, which could significantly affect product costs.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.30.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

1. Reduced environmental impacts of the California electricity supply, transmission, or distribution system
2. Increased public safety of the California electricity system
3. Increased reliability of the California electricity system
4. Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is from reduced environmental impacts of the California energy supply and distribution system. Secondary benefits would accrue from increased affordability of energy in California.

Demonstration that the thermochemical production of hydrogen can be readily carried out in an ionic liquid and devising alternative pathways to the implementation of the thermochemical cycle may lead to practical production of hydrogen from water using renewable energy sources such as solar. Reduced environmental impacts from natural gas production (used in the steam reforming production of hydrogen) and from electricity generation (used in the electrolytic production) are important, but unquantifiable, benefits that could enable development of a robust hydrogen fuel market in California.

Thermochemical hydrogen could have costs similar to those for residential natural gas for California customers in June 2009 of 89.8 cents per therm and slightly lower than the average for 2007-2008 of 126.0 cents per therm. In August 2010, Southern California Gas charged 66.1 cents per therm.[93] In some situations, enhancing a stream of natural gas with thermochemical hydrogen using a process like the cycles devised in this project could help reduce the cost of energy to the California ratepayer. Further, the process would be carbon free, which may be a benefit in the future. For example, if a carbon cost of $0.5/kg carbon were enacted (similar to the cap and trade costs of permits envisioned by the California Air Resources Board), natural gas consumers could realize savings of $500,000,000 in avoided taxes.

2.30.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

2.30.8.1 Marketing/Connection to the Market

The concept is not yet sufficiently developed to pursue market connections. The researchers have presented papers at American Chemical Society and American Chemical Engineering conferences.

2.30.8.2 Engineering/Technical

The researchers are investigating alternative reaction pairs.

93 www.socalgas.com/regulatory/tariffs/tm2/pdf/GR.pdf

2.30.8.3 Legal/Contractual

The concept is not yet sufficiently developed to pursue patents or legal and contractual partnerships with development partners. The researchers submitted an invention disclosure to Oregon State University's Office of Technology Transfer. Oregon State University may choose to submit patent application(s).

2.30.8.4 Environmental, Safety, Risk Assessments/ Quality Plans

Depending on the delivery mechanisms for hydrogen fuels, a number of environmental and safety issues may arise. If, as suggested by the researchers, the hydrogen is mixed with pipeline natural gas, pipeline embrittlement and flame properties at end use points are of concern. National standards for pipeline natural gas (including mercaptan odorizers) would have to be thoroughly evaluated and likely modified. Modifying national standards would likely take at least five to six years.

2.30.8.5 Production Readiness/Commercialization

The concept is not ready for commercialization.